

BASEMENT AND COVER RELATIONSHIPS IN
THE VESTRANDEN-GRONG-OLDEN REGION,
CENTRAL SCANDINAVIAN CALEDONIDES:
PETROLOGY, AGE RELATIONSHIPS, STRUCTURES,
AND REGIONAL CORRELATION.

by

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Basement and Cover relationships in the Vestranden-Grong-Olden Region , Central Scandinavian Caledonides: Petrology, Age relationships, Structures, and Regional Correlation.

Abstract

The Precambrian crystalline rocks, which constitute the basement beneath the Caledonian Allochthon, are well exposed in the Grong-Olden Culmination and in the Vestranden gneiss area of central Norway and Sweden. There are differences in lithologies, metamorphism, degree of Caledonian reworking and in the age pattern between the Grong-Olden Culmination and Vestranden.

The **Grong-Olden Culmination** consists mainly of approximately 1650 Ma old granites and rhyolites. These rocks were intruded by alkali-olivine dolerites around 1220 Ma ago. The dykes are similar to dolerites of the Central Scandinavian Dolerite Group (CSDG) occurring in the Precambrian terrains east of the Caledonides. In late Precambrian to Lower Palaeozoic time sediments of the Jämtland Super group were deposited on the Precambrian crystalline rocks of the culmination.

During the Caledonian orogenic event the area suffered deformation including thrusting and folding. The metamorphism reached middle amphibolite facies in the western and greenschist to lower greenschist facies in the central and southern part of the culmination. A nappe consisting of Precambrian crystalline rocks (the Basement Nappe), partly of the same type as those found in the culmination, were thrust over the core of the culmination and the metasedimentary cover of the Jämtland Supergroup. The metasediments were thereby incorporated into the thrust zones.

Remnants of these rocks can be traced in thrust zones along the margin of the Grong-Olden Culmination. In the Snåsa-Grong area in the westernmost part of the Grong-Olden Culmination, the thrust zone with its metasediments plunge westwards beneath the overthrust Basement Nappe. In this area the nappe comprises lithologies commonly found farther west in Vestranden. The thrust zone have not been found farther west. A Caledonian thrust relationship between the core of the Grong-Olden Culmination and the eastern part of Vestranden is thereby evident.

The major part of **Vestranden** is made up of migmatitic granitoid gneisses, augen gneisses and metabasites. More than 1800 Ma old granitic and tonalitic rocks occur in the northern half of Vestranden. One of these granites is the Geitfjellet granite south of Grong which yielded a U-Pb zircon age of 1823 Ma. This granite can, based on petrography, geochemistry, and age be correlated with Svecokarelian granites of the Revsund type occurring in north central Sweden. Rb-Sr data suggest that migmatites in the Geitfjellet granite may have formed around 1650 Ma.

In the southwestern Vestranden, high-pressure granulite rocks occur. Detailed investigations, including geothermometry and geobarometry, on sapphirine bearing basic rocks indicate PT conditions around 14.5 kbar and 850 °C. Sapphirine formed during retrogression, at low P_{H_2O} , to medium pressure granulite facies. This was followed by further retrogression at high P_{H_2O} connected to intense deformation and folding. During deformation, the major part of the

structures and primary features of the Precambrian crystalline rocks were obliterated. Minor, often lensoid areas with well preserved rocks escaped much of the deformation. One such area is the Granholvatnet lens, where two generations of migmatite veins occur and where coronitic rocks can be seen in the central part of the lens.

The Caledonian cover rocks have been studied in and correlated between two localities. These are the Snåsa Mega lens in the border zone between Vestranden and the Grong-Olden Culmination and Fosslia in western Vestranden. The former comprises the Offerdal, Särvi, Seve, Gula and Stören nappes of the lower, middle and upper Caledonian allochthons. Deformation, structure and metamorphism are discussed. The Fosslia occurrence can be based on lithological similarities and radiometric results be correlated with the Gula Nappe of the Snåsa Mega-lens. Both Gula units are intruded by granodioritic to tonalitic dykes which at Fosslia yielded a U-Pb zircon age of 430 Ma. Major deformation and amphibolite facies metamorphism retrograding granulite mineral assemblages took place in western Vestranden after c. 430 Ma.

Sveconorwegian rocks or deformation/metamorphism have so far been detected neither in Vestranden nor in the Grong-Olden Culmination. However, Sveconorwegian ages have been obtained in the Western Gneiss region farther south and in Caledonian nappes derived from areas west of Vestranden, suggesting that the "front of Sveconorwegian influence" passed, in pre-Caledonian time, to the south and to the west of Vestranden.

Introduction

The Ph. D. thesis includes seven papers which discuss different geological aspects of the Grong-Olden Culmination and the northern part of the Western Gneiss Region (Vestranden). The studies started originally within the framework of the Swedish Geodynamics Project (IGP), continued in the Caledonide Orogen Project (IGCP-CO) and have been completed during the International Lithosphere Project (ILP). All figures and tables referred to in this first chapter can be found in the different parts of the thesis. Most place names can be found in Figure 3 in paper II.

The geological research from the early seventies until now has shown that rocks derived from the Precambrian basement occur in most of the Caledonian Nappes. This shows that the basement was not only a passive substratum but that basement derived rocks also are an integral part of Caledonian nappe pile. Another evidence for an "active" basement is the occurrence of eclogites of Caledonian metamorphic age in the basement of western Norway. Formed from low pressure protholiths, these eclogites show that this part of the basement was depressed to considerable depths during the Caledonian continent-continent collision (Griffin et al. 1985).

Since the Vestranden basement formed the substratum of the Caledonian miogeocline, the area is of central importance for the Caledonian orogenic development. The PTt evolution recorded in Vestranden rocks can give important information about the accretionary and uplift history.

The pre-Caledonian relationships can partly be reconstructed and regional correlations with the Svecokarelian and the Southwest Scandinavian provinces in Sweden and in southern Norway can be done.

The Precambrian basement is almost continuously exposed from the Grong-Olden Culmination in the east to the Vestranden region in the west (Fig. 2, part 2) over a distance of about 200 km across the strike of the Caledonian mountain chain. The differences in lithologies, metamorphism and degree of deformation between Vestranden and Grong-Olden Culmination can easily be seen in the field. These differences could theoretically be explained in various ways; 1. they were established already in Precambrian time. 2. they are the result of a very intense Caledonian reworking of the westernmost basement; 3. a combination of 1 and 2; 4. Vestranden represents an exotic terrane accreted to the Baltoscandian margin in Caledonian time.

A main purpose of the thesis was to study the relationship between the Grong-Olden and the Vestranden regions and the basement-cover relationships in the border zone (Snåsa-Grong area).

The geological framework of the Norwegian and Swedish parts of the Grong-Olden Culmination is provided by maps published by the Norwegian and Swedish Geological Surveys respectively. Vestranden has never been mapped on a regional scale and the geophysical information is very limited. Therefore, to compare the regions the study had to be broadened to include also radiometric investigations and studies of metamorphism and basement-cover relationships in

Vestranden.

It has been possible to cover only a few of all the different aspects of basement geology and basement-cover relationships that can be studied within the Grong-Olden-Vestranden area. The investigations have therefore been concentrated to three areas. These are *the Olden Window* in Sweden, *the Snåsa-Grong area* and *the coastal districts in Vestranden*. The intention has been to focus upon some important aspects of regional interest rather than to give a very detailed picture of the geology of a limited area.

Two papers deal with geological aspects of the Grong-Olden Culmination (1,2), three papers consider the geology in the Snåsa-Grong transition zone between the Grong-Olden and Vestranden regions (2,3,4) and the geology of Vestranden is discussed in papers 4, 5, 6 and 7.

The thesis comprises the following papers.

I. Johansson, L., 1980: Petrochemistry and regional tectonic significance of metabasites in basement windows of the central Scandinavian Caledonides. *Geologiska Föreningens i Stockholm Förhandlingar*, vol.102, 499-514.

II. Johansson, L., This volume: The relationship between the Grong-Olden Culmination and the Vestranden gneiss area in the Caledonian basement of central Norway.

III. Andreasson, P.-G., & Johansson, L., 1982: The Snåsa Mega-lens, west-central Scandinavian Caledonides. *Geologiska Föreningens i Stockholm Förhandlingar*, vol. 104, pp. 305 - 326.

IV. Johansson, L., Schöberg, H., & Solyom, Z., This volume: Correlation of Proterozoic rocks across the Transscandinavian Belt: The Geitfjellet granite in Vestranden, Norway, an equivalent of the Svecokarelian Revsund granite in Sweden.

V. Johansson, L., Andreasson, P.-G., & Schöberg, H., This volume: An occurrence of the Gula Nappe in the Western Gneiss Region, central Norwegian Caledonides. Submitted for publication in *Norsk Geologisk Tidsskrift*.

VI. Johansson, L., & Möller, C., This volume: Formation of sapphirine during retrogression of a basic high pressure granulite, Roan, Vestranden, Western Gneiss Region, Norway. Submitted for publication in *Contributions to Mineralogy and Petrology*.

VII. Johansson, L., This volume: Mega-lenses and Scandian deformation in basement in the northern part of Western Gneiss Region, Vestranden, central Norwegian Caledonides. *Geologiska Föreningens i Stockholm Förhandlingar* (in press).

Summaries of the component papers

PAPER I

PETROCHEMISTRY AND REGIONAL TECTONIC SIGNIFICANCE OF METABASITES IN BASEMENT WINDOWS OF THE CENTRAL SCANDINAVIAN CALEDONIDES.

There are many dyke swarms of different age in the Baltic Shield (Gorbatshev et al. in press). They all indicate important time periods of extensional tectonic regimes. In the Caledonides, the Late Precambrian Ottfjället dolerites (Särv Nappe) is an important dyke swarm since these dykes were related to the rifting stage of the opening of the Iapetus ocean (Gee 1975, Solyom et al. 1979a). A relationship between the Ottfjället dykes and amphibolites of the Seve nappe was proposed by Strömberg (1969) and by Solyom et al. (1979b). The interest has been focussed on the regional distribution of Ottfjäll Dolerites and the question whether they intruded the Precambrian basement now exposed in the western windows and in the Western Gneiss Region, or not. An investigation of dykes intruding the basement of the Grong-Olden Culmination and the Tömmerås Window was therefore undertaken.

The Grong-Olden and Tömmerås metabasites occur both as dykes and as irregularly shaped bodies. In the Grong-Olden area, most dykes are approximately NNE-SSW oriented. In some places in the Olden Window, the dykes preserve the igneous mineralogy comprising olivine, clinopyroxene and plagioclase and opaque minerals.

The Olden metabasites can on geochemical grounds be subdivided into two groups (Olden I and Olden II groups). The Olden II group has higher Ti, Al, Mg and Sr and lower Fe, Rb, Nb and Zr contents than the metabasites in the Olden I group. There is a clear correlation between distribution in the field and the geochemistry. Almost all the Olden II samples were collected in the central part of the Olden window while the Olden I group were sampled all over the Olden window.

Different major element discrimination diagrams bring out an alkaline character while the trace element indicate a weak tholeiitic character of the Olden and Tömmerås samples. The Olden and Tömmerås metabasites are best classified as alkali-olivine basalts. The geochemical difference between the two Olden groups is less than the difference between the Olden groups and the Ottfjället and Seve metabasite groups. The alkaline chemistry of the Olden and Tömmerås samples is different from the tholeiitic character of most of the Ottfjäll metadolerites and the Seve metabasites. However in the Ottfjället dolerite group from the type area (Solyom et al 1979 a), there are a few samples with an alkaline chemistry. These Ottfjället dolerites can be separated from the Olden samples by their higher contents of Si, Ca, P, Nb and lower Fe content. Also in the Leksdalssvann group dolerites (Andreasson et al. 1979), which are correlatives to the Ottfjället dykes occurring in the Tömmerås Window, there are alkaline dykes which major element chemistry is

very close to that of the Olden I group. However, there are differences between the groups in the trace element chemistry; the Olden I samples having lower Nb, Sr and Zr than the Leksdalsvann dykes.

Instead it is possible to correlate the Olden and Tömmerås dykes with basic dykes occurring in the Precambrian basement east of the Caledonide front in Jämtland. The latter dykes belong to the very extensive CSDG group (Central Scandinavian Dolerite Group; Gorbatshev et al. 1979 b). There are clear similarities between the geochemistry, mineralogy, petrography and field appearance between the Olden-Tömmerås and the CSDG dolerites. The CSDG dolerites have been dated with the Rb-Sr method (Patchett 1978). The result suggests that the dykes intruded at approximately 1220 Ma. Dykes of this group occur not only in the Precambrian region to east of the Caledonides, in the Grong-Olden Culmination and in the Tömmerås window but possibly also in allochthonous Caledonian units interpreted as parts of the Seve nappe which had been derived from areas to the west of the present Norwegian coast. Mearns & Van Roermund (1985) reported about c. 1250 Ma old dykes in the Upper Allochthon of northern Jämtland.

The main conclusions are:

- The dykes occurring in the Olden and Tömmerås basement are alkali-olivine basalts with respect to the major elements and the mineralogy. A weak tholeiitic character is indicated by the trace elements.
- The dykes in the basement in the Olden and Tömmerås Windows are not related to the Ottfjället dykes in the type area at Ottfjället or to equivalent dykes in the Leksdalsvann Nappe in the Tömmerås area, or to the Seve metabasites at Mt. Sylarna.
- The dykes intruding the Olden and Tömmerås basement can be correlated with the c. 1250 Ma old Central Scandinavian Dolerite Group (CSDG)

PAPER II

THE RELATIONSHIP BETWEEN THE GRONG-OLDEN CULMINATION AND THE VESTRANDEN GNEISS AREA IN THE CALEDONIAN BASEMENT OF CENTRAL NORWAY.

The **Grong-Olden Culmination** is divided into two antiforms, the Olden Antiform trending approximately N-S and the E-W striking Grong Antiform. There are differences between the lithologies found in the Grong-Olden Culmination and those of the Vestranden area. The relationships between the two basement regions are best studied in the Snåsa-Grong area where Vestranden rocks border on the westernmost part of the Grong-Antiform. There is much less lithological variation within the Grong-Olden Culmination where well preserved granites, porphyries and dolerite dykes dominate. No migmatites or crosscutting

pegmatites occur. The only significant metamorphism that has influenced the rocks of the Grong-Olden Culmination is of Caledonian age.

In **Vestranden**, the most common lithologies are migmatitic granites, granodiorites and in some areas also tonalites. The Caledonian deformation transformed many coarse-grained granites to augen gneisses. Numerous basic rocks occur as dykes, fragments and boudins within the migmatitic gneisses. The metamorphic grade locally reached high pressure granulite facies conditions but most rocks are in amphibolite facies. Late Caledonian pegmatites intrude the gneisses and retrogressed the granulite facies country rocks.

Coarse-grained grey granites in Vestranden can be correlated with Svecokarelian granites of north central Sweden (paper IV). No signs of any Sveconorwegian metamorphism or deformation have so far been found in Vestranden. Neither have any Sveconorwegian intrusive rocks been found. However, Sveconorwegian metamorphism and intrusive activity has been detected in rocks derived from areas to the west of Vestranden.

During the Caledonian deformation and metamorphism, the Precambrian crystalline rocks in Vestranden, were folded together with nappes of the Caledonian allochthon. This caused a severe "Caledonization" of the Precambrian basement rocks. Vestranden can, based on magnetic and gravimetric data, be divided into a western and an eastern part where the former is characterized by a strong positive magnetic and gravimetric anomaly.

Granites and rhyolites in the basement of the Grong-Olden Culmination are overlain by Palaeozoic metasediment belonging to the Jämtland Supergroup (Gee 1975,1980). These rocks have been overthrust by a Basement Nappe partly consisting of the same type of rocks as those found below the thrust. The Basement nappe can tentatively be divided in two sub-units consisting of rocks of Vestranden type (Sandöla unit) and of Olden type (Lurudal unit) lithologies respectively. The thrust zone can be traced along the margin of the culmination. In the westernmost part of the Grong Antiform, the thrust zone disappears beneath overthrust Vestranden rocks which in turn are overlain by the Caledonian Nappe sequence in the Snåsa mega-lens (paper III). Rocks of the Vestranden type also occur in the Basement Nappe east and north of the Grong Antiform. This suggest that there is crustal shortening between the Grong-Olden Culmination and the Vestranden area.

Five phases of deformation can be distinguished in the Snåsa-Grong area. The first phase predated the Caledonian thrusting and is locally recorded as internal fabrics in garnets in the basement. The regional foliation which can be found in almost all rocks formed during the second deformation phase (D2). Isoclinal D2-folds are common in the thrust zones. The Caledonian nappe sequence was folded and refolded during the third (D3) and fourth (D4) deformation phases. A very prominent NW-SE trending lineation is coaxial with the major D3 folds such as the Snåsa and Flåtjern Synforms. The last discernible phase (D5) was of brittle character and responsible for numerous minor breccias in the Snåsa-Grong area. This phase is related to the block faulting along the major NE-SW lineaments to the north of the Trondheim fjord. Devonian basins in southwestern Vestranden are partially bounded by these faults.

Due to the limited variation in bulk compositions the granitic basement of the Grong Antiform is not well suited for detailed metamorphic studies. The metamorphic history is therefore best studied in the thrust zones fringing the Grong Antiform where the lithological variation is larger and where the tectonic processes and presence of fluids have enhanced mineral reactions. In the thrust zone, the regional D2 foliation is easily observed and the growth of different minerals in relation to this foliation can be studied here.

Kyanite, garnet and staurolite predated the regional foliation and suggest that the rocks have undergone middle amphibolite facies metamorphism prior to the development of the thrust foliation. Garnet, hornblende, phengitic white mica, biotite and epidote were stable during the D2 thrusting. After the thrusting had ceased, the D2 foliation was overgrown by chloritoid, garnet, biotite, actinolite and finally chlorite. These minerals represent epidote-amphibolite to greenschist facies conditions prevailing from late D2 to D5 deformation phases. The brittle deformation (D5) took at least partly place under zeolite facies PT conditions. Breccias are commonly cemented by stilbite, calcite, quartz and sometimes chlorite.

The main conclusions in this paper are:

- There are large differences in regard to lithology, metamorphism and to the degree and complexity of deformation between the Grong-Olden Culmination and the Vestranden areas.
- The rocks of the westernmost part of the Grong Antiform plunge down beneath gneisses of the Vestranden region.
- The tectonic relationship between the Grong-Olden Culmination and Vestranden implies crustal shortening and most likely also a disturbance of the metamorphic patterns.
- The thrust zones fringing the Grong-Olden Culmination contain remnants of Late Proterozoic to Palaeozoic metasediments of the Jämtland Supergroup. This shows that the thrusting and development of penetrative structures in the surrounding gneisses are Caledonian in age.
- The differences between the two regions with respect to lithological variation and metamorphism were to a large extent established long before the Caledonian orogenic event. The Caledonian tectono-metamorphism accentuated the difference by more intense reworking in Vestranden than in the Grong-Olden-Culmination.
- The front of strong Sveconorwegian reworking is located to the west of the Vestranden area.

PAPER III

THE SNÅSA MEGA-LENS, WEST CENTRAL SCANDINAVIAN CALEDONIDES.

Both the Grong-Olden and the Vestranden basement regions are overthrust by Caledonian nappes of the Lower, Middle and Upper Allochthons. The nappe sequence was studied in the Snåsa Mega-lens which occupies the northernmost part of the Trondheim depression. The mega-lens comprises five principal units belonging to the Middle (the Offerdal Nappe) and Upper Caledonian Allochthon (the Särvi Nappe, the Seve Nappes, the Gula Nappe and the Stören Nappe). The nappes represent different geotectonic environments. The Offerdal and Särvi Nappes consist mainly of feldspathic sandstones of Late Precambrian age, the latter nappe was intruded by the Ottfjället dolerite dyke swarm related to the rifting phase of the opening of the Iapetus Ocean (Solyom et al. 1979a). The Seve Nappes consist in the studied area of amphibolite facies mica schists and garnet amphibolites. Compared to the Seve Nappe the Gula Nappe is lithologically much more varied with calcareous schists, mica schists, marbles, graphite bearing schists, felsitic rocks, ultramafic rocks, garnetiferous ores and trondhjemitic to granodioritic dykes as the main lithologies. A tectonic break is recognized between the rocks of the Seve and the Gula Nappes. The Stören Nappe is not considered in the present paper.

The Middle and Upper Allochthons are underlain by intensely deformed Precambrian gneisses of the Lower Allochthon. Some of these gneisses can be correlated with similar lithologies in the Grong-Olden Culmination and others with rocks found in Vestranden. The lithologies and metamorphism in and the structural history of these units are discussed in paper II.

The structural history recorded in the Snåsa Mega-lens comprises 5 events including late steep faulting. D1 is seen only in the Seve and Gula rocks and may be early Scandian (Mid-Silurian to Early Devonian) or older. D2 to D5 are common to all the nappe units and to the basement below and are outlined in the summary of the second paper above.

After thrust emplacement, the entire tectonostratigraphy was folded by the Snåsa and Flåtjern Synforms and by the Kolås fjell Antiform. These major folds are gentle in the southeast but become tighter towards northwest. In the Geitfjellet area, approximately 10 km northwest of the Flåtjern Synform, the folds are tight to isoclinal. The axial planes of major folds are overturned in the northwestern areas. The folding was accompanied by coaxial intense stretching giving rise to NE-SW oriented lineations in all units and in basement at least in the western parts of the Snåsa-Grong area. This lineation is very prominent in Vestranden but loses much of its significance eastwards toward the Grong Antiform.

Metamorphism after the thrusting was probably of short duration. It reached lower amphibolite facies but did not obliterate earlier metamorphic parageneses in the nappes. The nappe succession represents an inverted metamorphic gradient with amphibolite facies rocks resting on rocks of greenschist facies grade. The highest metamorphic grade, medium amphibolite facies, is recorded in rocks of the Gula

Nappe.

The main conclusions are:

- The principal tectonostratigraphy of the Swedish Caledonides can be established in the northwestern Trondheim region.
- There is a marked increase in ductility of deformation and in the prominence of the NE-SW trending stretching lineation across the Snåsa-Grong border zone between Vestranden and the Grong-Olden Culmination.
- Metamorphic breaks occur between the nappe units still as far west as at the border to Vestranden.
- The nappes travelled together in composite units subjected to extreme stretching.
- The Gula and Seve Nappes preserve evidence of a pre- or possibly early Scandian metamorphic high-grade event.

PAPER IV

CORRELATION OF PROTEROZOIC ROCKS ACROSS THE TRANS-SCANDINAVIAN BELT: THE GEITFJELLET GRANITE IN VESTRANDEN, NORWAY, AN EQUIVALENT OF THE SVECOKARELIAN REVSUND GRANITE IN SWEDEN.

In the eastern and northwestern parts of Vestranden, coarse-grained grey granites are common. These rocks were commonly deformed to augen gneisses. On Geitfjellet, the coarse granite is partly migmatitic. Petrographically similar granites are not found in the Grong-Olden Culmination. A migmatite forming event has not been recorded in the granites in the nearby Grong-Olden Culmination.

A U-Pb zircon- and a Rb-Sr-dating of the Geitfjellet granite was made to assess the intrusion age of the granite and to obtain information about the age of the migmatite forming event.

The Geitfjellet granite has the shape of a slice within a complex of red and grey medium to fine-grained migmatitic gneisses. An undisputable tectonic contact between the granite and the surrounding gneisses has not been found. The deformation of the granite varies considerably from almost undeformed granite to augen gneiss. Most of the deformation structures are of Caledonian age. The granite consists of quartz, K-feldspar, plagioclase, biotite. Garnet and muscovite are minor phases and apatite, diopside, zircon and opaque minerals are accessory minerals.

The granite was sampled both for the radiometric investigation and for a restricted geochemical study. The geochemical results show that the Geitfjellet granite is a slightly peraluminous granite and thus different from the highly evolved

I-type granites of the Grong-Olden Culmination.

A special study using abrasion techniques and electron microscopy of the zircons was undertaken. Most zircons have three "growth zones". These include an innermost euhedral core with a weak compositional zoning followed by a slightly darker part which is *concordant* to the core. The latter zone is probably a continued growth of the zircon core but with a less pure zircon. The third growth zone is present in many but not all zircons and consists of a thin rim which is *discordant* to the inner growth zones. This zone consists of pure zircon.

The data was plotted in a concordia diagram and the an age of 1775 ± 70 Ma was obtained. Due to the complex growth zoning, four zircon fractions were abraded and reanalysed. The new age based on 8 fractions is 1823 ± 21 Ma. If only data obtained from the internal parts of the zircons are regressed the resulting age is 1830 ± 26 Ma.

The Rb-Sr dating was made on 10 samples of which three were taken from migmatitic neosomes in the granite. The data from the three migmatitic samples clearly indicate a disturbance of the Rb-Sr system. The age of this disturbance is not well constrained but may have occurred around 1650 Ma. The data of the other samples yield an age of 1784 ± 11 Ma. These results show that the Geitfjellet granite is older than the Olden granite.

The Geitfjellet granite can be correlated with the grey coarse-grained Revsund granites of similar age in Jämtland and Västerbotten in north central Sweden. The Revsund granites intruded supracrustal rocks of the Svecokarelian Bothnian Basin in the time interval 1770 - 1790 Ma (U-Pb zircon dating, no abrasion of zircons). The supracrustal comprises among other rocks pelites, pillow lawas, and black shales. The Bothnian Basin may represent an outer arc accretionary prism environment (Wilson et al. 1985).

A correlation between the Geitfjellet granite and granites of the Revsund type is supported not only by age relationships but also by similarities in petrography, geochemistry, and in initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios. Granites of the Revsund-Geitfjellet type can also be found in northern and northwestern Vestranden and in the Börgefjell Window halfway between Västerbotten and Tröndelag.

It is also possible that "Caledonized" remnants of the Svecokarelian supracrustal rocks of the Bothnian Basin type occur in Vestranden.

The main conclusions are:

- The Geitfjellet granite is approximately 1825 Ma old and can be correlated with Svecokarelian granites of the Revsund type intruding the Bothnian Basin in north central Sweden.
- Large areas in the northern half of Vestranden with granitic to tonalitic rocks are substantially older than the granites and rhyolites of the Grong-Olden Culmination.
- Also supracrustal rocks of the type occurring in the marine environment of the Bothnian Basin may be present in Vestranden.

PAPER V

AN OCCURRENCE OF THE GULA NAPPE IN THE WESTERN GNEISS REGION, CENTRAL NORWEGIAN CALEDONIDES

In many places in the Vestranden area, minor units of supracrustal rocks occur. In most cases, it is difficult to know whether these units are allochthonous Caledonian cover units or if they are Precambrian supracrustals forming part of the Precambrian basement. It was earlier believed that the Vestranden region was the "core" of the Caledonian orogen and it was commonly inferred that the almost complete "Caledonization" made it impossible to recognize and identify Caledonian allochthonous nappes in Vestranden.

At Fosslia in western Vestranden, an about 800 m thick unit of supracrustal rocks occur. These rocks were folded together with the surrounding migmatitic basement. The rock sequence comprises micaceous gneisses, quartz veined gneisses, quartz-feldspar gneisses, felsites, amphibolites, graphitic schists, and mica schists. There are also minor sulphide mineralizations with a characteristic association of pyrite/pyrrhotite and manganese rich garnet.

These rocks and the sulphide-garnet association are typically found in rocks of the Gula Nappe in the Snåsa Synform (paper III). A correlation between the rocks of the Gula Nappe and the Fosslia rock are further strengthened by a U-Pb zircon dating on a granodioritic dyke intruding the Fosslia supracrustal rocks. The dyke is restricted to the cover sequence. The zircons are varying in shape and very rich in uranium due to small inclusions of uraninite. The age is 430 ± 12 Ma and is interpreted as a minimum age of intrusion of the dykes. This age is slightly lower than the ages reported for trondhjemite dykes in the Gula Nappe in the Trondheim Nappe Complex (Klingspor & Gee 1981). The Fosslia dykes and supracrustals were metamorphosed and deformed under amphibolite facies conditions.

The main conclusions are:

- The Fosslia cover unit can be correlated with rocks of the Gula Nappe in the Snåsa synform.
- The major deformation and folding of the Fosslia rocks and the underlying migmatitic basement took place in Scandian time after the intrusion of the dykes and the thrust emplacement of the rock onto the basement.
- It is possible to recognize and identify allochthonous Caledonian cover units in Vestranden despite the intense metamorphism and deformation.

PAPER VI

FORMATION OF SAPPHIRINE DURING RETROGRESSION OF A BASIC HIGH PRESSURE GRANULITE, ROAN, VESTRANDEN, WESTERN GNEISS REGION, NORWAY.

The westernmost part of Vestranden is different from the rest of Vestranden with respect to its higher metamorphic grade and to the marked positive gravimetric and magnetic anomaly of the area.

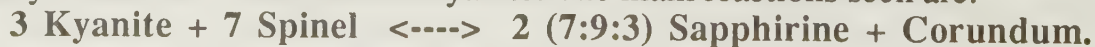
In the Roan area in the westernmost part of Vestranden, granulite facies rocks occur in restricted areas surrounded by rocks of amphibolite facies. This area is well suited for detailed studies of the metamorphic evolution of western Vestranden. Granulite facies rock have so far not been reported elsewhere in Vestranden. The granulite mineral assemblages occur in the cores of metabasites as well as in the surrounding gneisses. Prograde metamorphism resulting in high-pressure granulites is recorded as garnet-clinopyroxene coronas around primary magmatic plagioclase, as prograde compositional zoning of garnets and in inclusions in the garnets. Retrogression to amphibolite facies was widespread. The existence of primary magmatic phases and textures in close proximity to high-pressure granulites in various stages of retrogression strongly underline the lack of regional scale equilibrium during both the peak metamorphism and the subsequent retrogression.

Metamorphism is best studied in metabasites in Kråkfjord and Brandsfjord. The rocks consist mainly of clinopyroxene, garnet, and kyanite. Some parts are also rich in orthopyroxene. The rock is characterized by high $Mg/(Mg+Fe^{2+})$ ratios (0.77-0.86) and high Al, Ca, and Cr contents. A discrete layering possibly of magmatic origin can be observed.

The metamorphic study is focussed on the retrogression at low P_{H_2O} of the high-pressure mineral assemblage garnet-clinopyroxene-kyanite to a medium-pressure granulite consisting of orthopyroxene, spinel, sapphirine, plagioclase and corundum. This "dry and early" retrogression is then followed by introduction of H_2O and severe amphibolitization.

The first step is the breakdown of the pyrope rich garnet to form orthopyroxene-spinel-anorthite symplectites. Also the clinopyroxene-kyanite pair became instable and reacts to form corundum, plagioclase and orthopyroxene. Oligoclase and orthopyroxene fringe the clinopyroxene while the kyanite is rimmed by corundum and anorthite. All secondary minerals occur as symplectites. The plagioclase is strongly zoned with the most sodium rich plagioclase close to remnants of clinopyroxenes.

Sapphirine is a third generation mineral formed by reactions between the secondary breakdown minerals and kyanite. The main reactions seen are:



The corundum is probably partly incorporated in the sapphirine which is more aluminous than the 7:9:3 end member composition

(corresponding to 7 MgO : 9 Al₂O₃ : 3 SiO₂).



This reaction has been observed in experiments (Schreyer 1967).

PT estimates were made on the clinopyroxene-garnet-kyanite and orthopyroxene bearing rocks using garnet-clinopyroxene, garnet-orthopyroxene and two pyroxene thermometry. The pressure was estimated by garnet-orthopyroxene barometry. The results indicate peak (?) PT conditions around 870 °C and a pressure of 14.5 ±2 kbar. These estimates correspond rather well with PT estimates obtained from Caledonian eclogites in the westernmost part of Western Gneiss Region. However, a correlation with a Precambrian granulite forming event cannot be excluded.

The main conclusions are:

- High pressure granulite rocks occurring in the Roan area indicate temperatures around 870 °C at 14.5 kbar.
- The occurrence of prograde, peak and retrograde parageneses within one and the same metabasite strongly reflects the lack of equilibrium on a regional scale.
- High pressure granulite parageneses were replaced by medium pressure granulite assemblages under low P_{H₂O} conditions.
- Sapphirine was mainly formed in two reactions involving orthopyroxene and spinel formed by the breakdown of garnet and the two alumina rich minerals kyanite and corundum.

PAPER VII

MEGA-LENSES AND SCANDIAN DEFORMATION IN BASEMENT IN THE NORTHERN PART OF WESTERN GNEISS REGION, VESTRANDEN, CENTRAL NORWEGIAN CALEDONIDES.

This short paper describes an important tectonic feature in Vestranden. The rocks of the western part of Vestranden have undergone very intense deformation in some areas leading to an almost complete reworking of the rocks. The reworking is characterised by a very intense shearing, isoclinal folding and refolding. Older structures such as migmatite veins were attenuated, basic dykes were strongly flattened and isoclinally folded. This deformation led to the formation of a large scale compositional banding in which the bands vary from metres to hundreds of metres in thickness. Banding and isoclinal folds with wavelengths up to at least 2 kilometres are seen on aerial photos. Despite this extreme deformation and reworking lens-shaped areas with less deformed rocks occur bounded by the

intensely sheared banded gneisses. One such lens is the Granholvatnet lens north of the Roan peninsula (paper VI). The lens strikes E-W and is about 500 m thick and 2800 m long in the present erosion surface.

In the internal part of the lens the rocks are much less deformed than along the margins of the lens. One generation of migmatite veins are irregularly distributed while another occurs in the axial planes of minor folds. There are also well preserved coronitic basic rocks in the lens. Along the margins of the lens, all basic rocks were amphibolitized. This suggests that major deformation forming the banding also retrogressed earlier high PT parageneses (see paper V, VI). The occurrence of allochthonous Caledonian cover units (paper V) within the banded and migmatitic basement strongly suggests that this deformation is Scandian in age.

The main conclusions are:

- Less deformed basement with preserved older structures and mineral parageneses occur as lensoid domains in western Vestranden.
- High grade metamorphism predated the intense regional deformation seen outside the tectonic lens.
- The intense regional deformation is most likely of Scandian age.

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PAPER I

PETROCHEMISTRY AND REGIONAL TECTONIC SIGNIFICANCE OF METABASITES IN BASEMENT WINDOWS OF THE CENTRAL SCANDINAVIAN CALEDONIDES.

Leif Johansson

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PAPER II

THE RELATIONSHIP BETWEEN THE GRONG-OLDEN CULMINATION AND THE VESTRANDEN GNEISS AREA IN THE CALEDONIAN BASEMENT OF CENTRAL NORWAY.

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THE RELATIONSHIP BETWEEN THE GRONG-OLDEN CULMINATION AND THE VESTRANDEN GNEISS AREA IN THE CALEDONIAN BASEMENT OF CENTRAL NORWAY.

L. Johansson

Abstract.

The basement beneath the Caledonides of south and central Norway is extensively exposed in the Grong-Olden Culmination and in the Western Gneiss Region. From the northernmost part of the Western Gneiss Region, the Vestranden area, the basement is eastwards continuously exposed into the Grong-Olden Culmination.

Vestranden is a lithologically complex area with granites, granodiorites, tonalites and basic rocks. Supracrustal rocks of both Precambrian and Caledonian origin also occur. Radiometric datings of Vestranden granitoids show that the rocks to a large extent are of Svecokarelian age. The Vestranden rocks have undergone at least two migmatite forming events of which one is Caledonian. Rocks derived from areas to the west of Vestranden were influenced by the Sveconorwegian orogeny while in rocks of the Vestranden proper no such influence has been detected so far. During the Caledonian orogeny the rocks of the Vestranden were intensely deformed and metamorphosed. In the westernmost parts, metamorphism reached granulite facies conditions. The Caledonian intrusive activity is restricted to pegmatite dykes.

The Grong-Olden Culmination consists of granites and rhyolites and is lithologically monotonous compared to the Vestranden area. Radiometric datings of rocks of the Grong-Olden Culmination suggest that these formed around 1650 Ma ago and therefore are younger than most of the Vestranden rocks. The former rocks were only affected by the Caledonian deformation and metamorphism. No migmatites or Caledonian pegmatites are found in the core of the Grong-Olden Culmination. The granites and rhyolites of the Grong-Olden Culmination can be correlated with similar rocks of the Transscandinavian Belt in southern and west-central Sweden.

The Precambrian rocks were overlain by Palaeozoic metasediments of the Jämtland Supergroup. These rocks are now found as thin remnants in thrust zones fringing the culmination. The metasediments are overthrust by a nappe consisting of Precambrian gneisses. This "Basement Nappe" is tentatively divided into two tectonic subunits; one with rocks of the Grong-Olden type (Luru unit) and the other of rocks similar to the lithologies found in Vestranden (Sandöla unit). The relation between the Grong-Olden Culmination and Vestranden has been studied in the Lurudal-Sandöla area which is a transition zone between the two regions.

The deformational history of the Lurudal-Sandöla area is divided into five phases. The first phase predated the Caledonian thrusting; the second was contemporaneous with the thrusting; the third and fourth phases involved refolding and retrogressive metamorphism of the nappe sequence; the last phase was characterized by brittle deformation during lower greenschist and zeolite facies

conditions.

The thrust zone with Palaeozoic metasediments disappears beneath an overthrust part of Vestranden. This implies crustal shortening between the Grong-Olden Culmination and the Vestranden region. The extent of this shortening is unknown but the occurrence of Caledonian nappe cover in the Vestranden area limits the allochthoneity. There are no features to suggest that the Vestranden is a foreign crustal block emplaced during the Caledonian continent-continent collision. Instead, Vestranden fits into the Precambrian pattern of the Baltic Shield.

Introduction

In the Scandinavian Caledonides, the Precambrian basement beneath the Caledonian nappes is exposed in many windows along the mountain chain (Fig 1). In the central Caledonides, a virtually complete transversal basement section is provided by three of the windows, the Grong-Olden Culmination, the Tömmerås Window and the Vestranden gneiss region. The Grong-Olden Culmination and the Vestranden region permit continuous observation of basement lithologies and tectonics along a profile extending for a distance of 200 km from the terrain of far-travelled nappes in Sweden to the high-grade basement along the Atlantic coast of Norway.

The Grong-Olden and Vestranden Windows thus play an important role both in the study of Caledonian basement-cover relationships and in the interpretation of the pre-Caledonian accretionary growth of the Baltic Shield. While numerous studies have treated the structural and metamorphic geology of the Caledonian allochthon in the Central Scandinavian Caledonides, only a few have focussed on the tectonic and metamorphic relationships within the basement. Previous basement studies have considered either the intensely deformed and metamorphosed western regions, i.e. mainly the Western Gneiss Region (for a review see Cuthberth et al. 1983), or have dealt with the much less deformed and metamorphosed eastern windows such as the Olden Window (Stephansson 1976, Johansson 1980, Troeng 1982, Stuckless et al. 1982, Lindquist 1983, Stel 1984, Talbot & Sjöström 1984) and the Tömmerås Window (Springer-Peacey 1964, Gee 1979, Andreasson 1980, Lindqvist & Johansson in prep.).

The purpose of this paper is to discuss the pre- and post-Caledonian relationship between the eastern basement (Grong-Olden Culmination) and the western basement (Vestranden region). Recent work in the Precambrian craton of Scandinavia suggest that these two regions belong to two different major crustal segments of the Baltic Shield (Gorbatshev 1985). The Precambrian relationships between the crustal segments have been overprinted by the Caledonian tectonothermal event, but can still be partly reconstructed.

The relationship between the two segments after the Caledonian deformation can be studied in the Lurudal-Sandöla area, a narrow basement corridor separating the Trondheim and Grong Nappe Complexes (Fig. 2).

Different models have been proposed for the relationship between the Vestranden area and the Grong-Olden Culmination. Fundamentally, there exist two

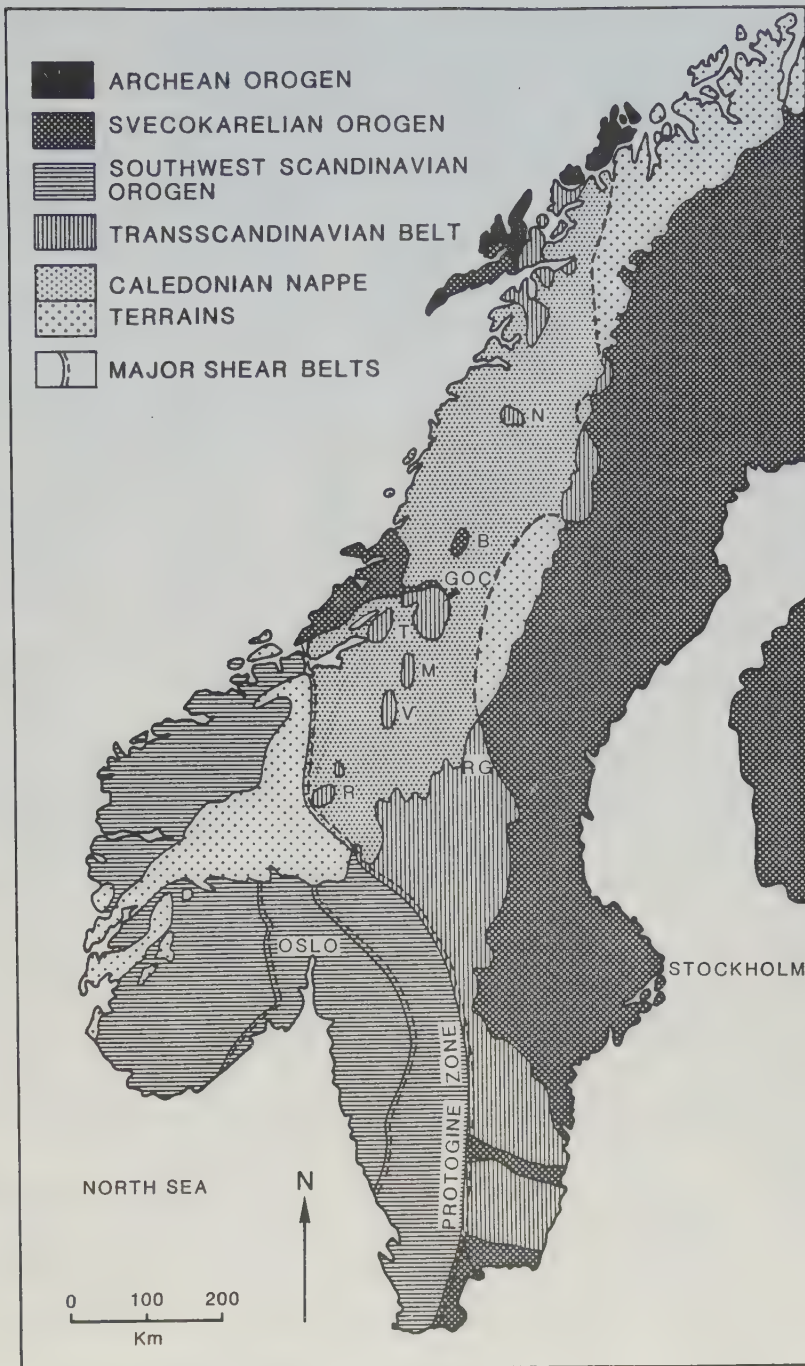


Fig. 1. Simplified map of the orogens of the western Baltic Shield essentially according to Gorbatshev (1985). GOC = the Grong- Olden Culmination , T = the Tømmerås Window, M = the Mullfjäll Window, V = the Vigelen Window, R = the Rondane Window, B =the Börgefjell Window, N = the Nasafjell Window. TA = Tännäs augen gneiss, RG = Rätan Granite

different kinds of models which can be described as the *continuous* and the *discontinuous* ones. The former is seen on the maps by Høltedahl & Dons (1960) and Ramberg (1966, 1967, 1977, 1981). It describes a gradual continuous increase in the intensity of Caledonian metamorphism and deformation in the basement from east to west. The transition from the Grong-Olden basement to Vestranden type basement is here thought to be an entirely Caledonian process. It is therefore often described as a "caledonization". According to this concept, all thrust planes, mylonites and other primary features seen in the east have been destroyed by the intense metamorphism and deformation in the western areas. Consequently, it has been considered impossible or very difficult to discriminate between the allochthonous Caledonian cover units and the basement in the westernmost areas.

The *discontinuous* model emphasise the tectonic relationship between the eastern and western basement areas. This model is applied in the maps of Törnebohm (1896) and Foslie (1958, 1959, 1960). These maps show a basal thrust along the margin of the Grong-Olden Culmination which separates the lowermost parautochthonous basement from nappes partly made up of similar rocks. This basal thrust also indicates a possible shortening of the basement and telescoping of the Caledonian metamorphic patterns. Most geologists familiar with the area have supported the discontinuous model (Oftedahl 1956, Gee 1975, 1980, Roberts 1978, Andreasson & Johansson 1982, and others).

Still another and completely different model was proposed by Mykkeltveit et al. (1980). While the models mentioned above concern relationships within the Baltic Shield, these authors infer that the Western Gneiss Region is part of an American plate accreted to the Baltic Shield during the continent-continent collision phase of the Caledonian orogeny. This model is based on the existence of a seismic low-velocity zone beneath the Western Gneiss Region (Kaneström 1977, Mykkeltveit et al. 1980). Mykkeltveit et al. (1980) interpreted the low-velocity zone as a suture occupied by eugeoclinal, low-grade metasediments squeezed between the Baltic Shield basement and the assumed American plate. In their model, the Vestranden area represents the American plate and the Grong-Olden basement the margin of the Baltic Shield.

In the present paper, the general geology of the *Grong - Olden Culmination* and the *Vestranden gneiss area* are first treated separately. Then follows a description of the geology of the *Lurudal-Sandöla transition zone* between these two areas and a synthesis of the relationships. The place names mentioned in the text can be found in Figs. 1 and 3.

The Grong-Olden Culmination.

The Grong-Olden Culmination is a composite structure made up by two antiforms trending ENE-WSW and NNW-SSE, respectively (Fig. 2). The antiform trending ENE-WSW occupies the northern part of the culmination and is called the Grong Antiform, while the NNW-SSE trending Olden Antiform dominates the central and southern parts of the culmination. The internal relationships between these antiforms have been discussed by Støl (1984). Together with other

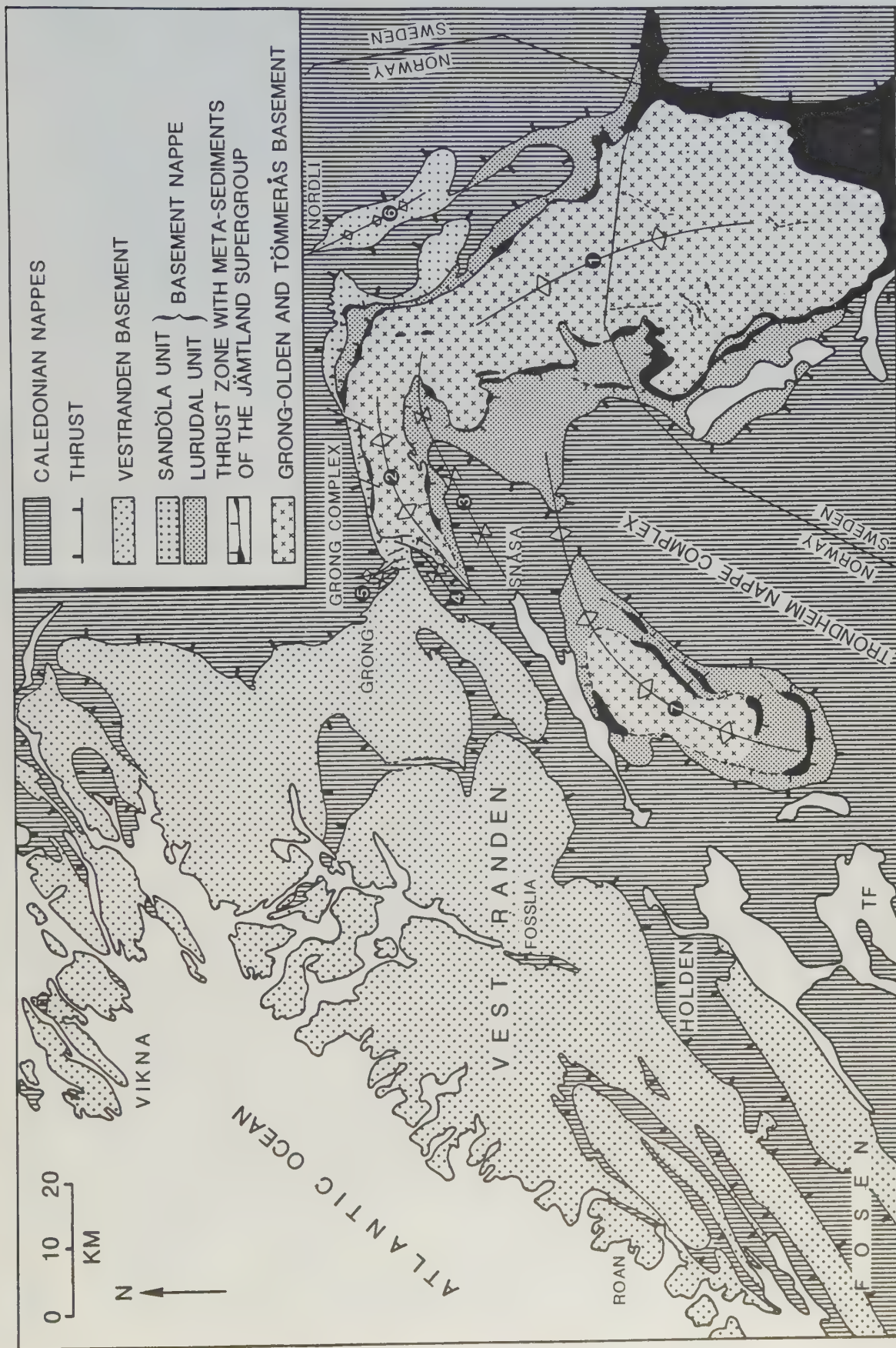


Fig. 2. Generalized map of the geology of northern Trøndelag. 1 = the Olden Antiform; 2 = the Grong Antiform; 3 = the Snåsa Synform; 4 = the Flåtjern Synform; 5 = the Trangen Synform-Antiform pair; 6 = the Nordli Antiform; 7 = the Tømmerås Antiform. TF = the Trondheimfjord; H = Holden.

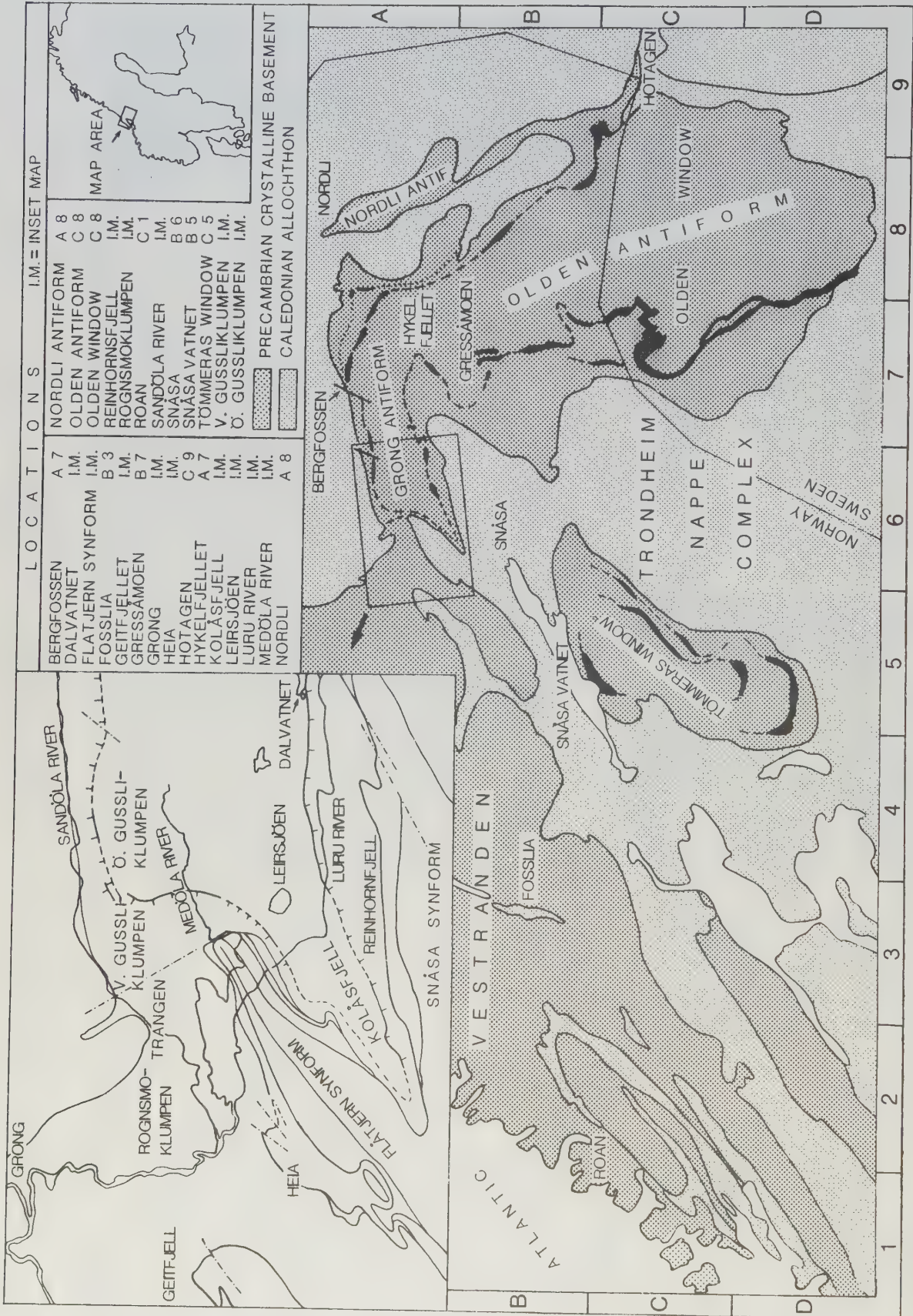


Fig. 3. Map showing the localities mentioned in the text. The localities in the Lurudal-Sandöla area are shown in the detailed inset map. Precambrian crystalline basement also includes parautochthonous and allochthonous basement derived units.

Precambrian rocks of the Baltoscandian margin, the Grong-Olden Culmination was overlain by Late Precambrian to Ordovician sediments. Metamorphosed remnants of these sediments are now found along minor thrusts in the central parts of the culmination as well as in a major zone of thrusting along the margin of the culmination (Fig. 2). The metasedimentary rocks in the different localities generally consist of incomplete successions comprising limestone/marble, quartzite, phyllite, and black shale. In the thrust zones, these rocks are squeezed in between slices of Precambrian rock. Atop the metasedimentary rocks is a nappe (the Basement Nappe) partly consisting of the same lithologies as those found beneath the thrust. The Grong-Olden Culmination is therefore best described as three separate sub-units comprising the *core* of the culmination, the thrusts and their *metasediments* and the *Basement Nappe* which was thrust over the culmination. The terms "basement" and "basement nappe" are here used in a wide sense covering not only autochthonous rock units but also reactivated older basement rocks now appearing as thrust sheets in the Caledonian nappe pile. The definition of "basement" has been discussed by Hatcher (1983).

The core of the Grong-Olden Culmination. - The core of the Grong-Olden culmination is lithologically monotonous. It is made up of granites and terrestrial volcanic rocks, dominated by rhyolites. Dacitic rocks are also present in subordinate amounts. These volcanic rocks are associated with fine-grained microgranites, which possibly represent hypabyssal equivalents of the effusives (Troeng 1982). Among the partly well preserved metavolcanic rocks, agglomerates and other pyroclastic rocks are occasionally found (Fig. 4).

The granites form large massifs as well as minor bodies. Geochemically, they are mostly highly evolved alkali granites (Stuckless et al. 1982, Troeng 1982, Stel 1984). From the northeastern part of the culmination, Stel (1984) reported similar alkali feldspar granites. Foslie (1958), however, mapped two restricted areas of "quartz poor dark granite" in the central part of the culmination. Both the granites and the supracrustals were intruded by dolerite dykes and by gabbros associated with ultramafic rocks (Johansson 1980, Zellman & Johansson 1984).

Stuckless et al. (1982) dated the Olden granite and an associated uranium mineralization in the Hotagen area, in the southeastern part of the Grong-Olden Culmination. Their results suggest that the granite formed around 1650 Ma ago and that the U mineralization formed as a result of the Caledonian metamorphism and brittle deformation 420 Ma ago. The latter age is also supported by the 418 Ma K-Ar age on biotite reported by Klingspor and Troeng (1980). Some of the mafic dykes of the Grong-Olden Culmination can on geochemical grounds (Johansson 1980) be correlated with 1250 Ma old dolerites (Patchett 1978) occurring in the basement east of the Caledonian front. However, preliminary palaeomagnetic results (Zellman & Johansson in prep) indicate that some of the basic rock may be still older. They possibly intruded in connection with the formation of the granites and supracrustals about 1650 Ma ago.

The rocks in the core of the Grong-Olden Culmination are part of a belt of granites and volcanites extending from southern Sweden to northern Norway 1). This belt has been termed the Transscandinavian Granite-Porphyry Belt



Fig. 4. Well-preserved volcanic rock with pyroclastic fragments (at the arrows) from Hykelfjellet (Fig. 3) in the core of the Olden antiform. The length of the hammer is 60 cm.



Fig. 5. Thin marble (at the arrow) within a minor thrust at Hykelfjellet (Fig. 3) in the core of the Olden antiform. The length of the hammer is 60 cm.

(Fig.1 ; Transscandinavian Belt in the following text; Gorbatshev 1980,1985).

The granites and porphyries of the Transscandinavian Belt were formed during a long period of time between 1790 and ≤ 1700 Ma ago (Wilson 1982, Gorbatshev 1985, Patchett et al. 1986). Results from a study by Åberg and Persson (1984) suggest that granites of this belt may have started forming as early as c. 1830 Ma ago. The granites were thus not emplaced during a single magmatic event. Regional aspects and more detailed information about the Transscandinavian Belt can be found in Gorbatshev (1980), Nyström (1982), Wilson (1982) and Wilson et al. (1984), Patchett et al. 1986).

Thrust zones and metasedimentary cover. - The Early Palaeozoic sedimentary rocks, which occur as remnants covering parts of the basement of the Grong-Olden Culmination, belong to the Jämtland Supergroup (Gee 1975). These rocks contain the major decollement zone of the east central Caledonides. Apart from small outcrops associated with the minor thrusts in the central part of the Grong-Olden Culmination (Fig. 5), most remnants of Palaeozoic metasediments occur within the large thrust zone fringing the culmination.

In general, only a few metres of cover metasediments are preserved in the thrust zones where they often occur as intensely deformed lensoid bodies. Similar relationships are found in most windows in the Caledonian mountain belt such as the Nasafjell, Börgefjell and Tömmerås Windows. In most places along the Grong-Olden Culmination, the metasediments are considered to be parautochthonous or allochthonous, but in the Hotagen (Walser 1980) and possibly also in the Gressåmoen areas (Gee 1974) autochthonous metasediments including basal conglomerates are present. While no fossils have been found in the metasediments along the margin of the Grong-Olden Culmination, the lower Palaeozoic metasediments can be traced into fossiliferous areas in Jämtland. A graphitic black shale of middle Cambrian to Tremadocian age is of particular interest since its high contents of U, Mo and V permit its identification elsewhere in the Scandinavian Caledonides (Gee 1980).

Where the metasedimentary rocks were intensely deformed, the quartzite is best preserved, whereas the marble and the black shales commonly were cut out tectonically. In many places, the metasediments are absent and the overriding nappe is thrust directly onto the underlying granitic rocks, which in such cases were transformed into quartz-muscovite and quartz-epidote schists (phyllonites). The thickness of the phyllonite dominated thrust zones varies considerably ranging from a few metres to nearly 300 m southeast of Östre Gussliklumpen (Fig. 3). A gradual development of increasingly more phyllonitic rocks can be seen as one passes from the core of the culmination towards the thrust zone.

The Basement Nappe. - As mentioned above, this nappe consist largely of rocks of the type found in the core of the culmination. Along the southwestern and western margins of the Olden Antiform and the southern side of the Grong Antiform, the nappe is composed of rhyolites and granites similar to those in the core of the culmination. West and north of the Grong Antiform, the lithologies are more varied. Stel (1984) described the rocks in the Nordli area and showed a clear geochemical difference between the alkali-feldspar granites of the core of the

Grong-Olden Culmination and the rocks occurring in the nappe. The latter have normative monzodioritic to granodioritic compositions. This difference between the core and the nappe cannot be explained by element mobility during the metamorphism and the intense deformation. The whole Basement Nappe therefore can not be derived locally from a basement source of the Grong-Olden core type.

The nappe thrustured over the Grong-Olden Culmination can tentatively be divided into two subunits. A lower part, the *Lurudal unit*, consists of lithologies of a type found in the core of the Grong-Olden Culmination, whereas an upper part, the *Sandöla unit*, has much stronger lithological variation. The Sandöla unit contains augen gneisses of different types, granites, granodiorites, monzodiorites, and fine-grained gneisses rich in plagioclase. The Sandöla unit resembles the lithologies occurring farther west in the Vestranden area.

Deformation and metamorphism. - The fundamental tectonic status of the Grong-Olden Culmination is unclear. It is not known wheather the core of the Grong-Olden Culmination is allochthonous (Asklund 1938, Talbot & Sjöström 1984, Hossack 1984), parautochthonous (Gee 1975, Gee & Zachrisson 1979) or autochthonous (Stephansson 1976). No geophysical data are available to solve this problem. According to Talbot & Sjöström (1984), the granites and supracrustals show an approximately SSE trending Svecokarelian fabric. Also Troeng (1982) noted the occurrence of Precambrian deformation or at least deformation predating Caledonian thrusting. Numerous minor shear zones occur within the core of the Olden Antiform. The rocks in the western part of the Olden Antiform generally show more ductile deformation than the rocks in the eastern part.

Faulting is important in the Grong Antiform. At Bergfossen, the margin of the Grong Antiform is displaced by a sinistral fault with at least 1 km of displacement (Fig. 3). Also in the northeastern areas, the tectonostratigraphy is disturbed by faulting (Stel 1984).

The metamorphic history of the Grong-Olden basement is poorly known. In the southernmost part of the Olden Antiform and in Hotagen (Fig. 3), illite crystallinity investigations by Kisch (1980) and Lindqvist (in prep.), and studies of the incoming of biotite (Lindqvist 1983) are in accordance with garnet-biotite thermometry (Harrisson 1979) suggesting peak temperatures of 350 - 400 °C. Stel (1984) and Aukes et al. (1979) report greenschist facies conditions in the eastern part of the Grong Antiform. Near Östre Gussliklumpen (Fig. 3), further west in the same antiform, staurolite, garnet and kyanite are found within the zone of thrusting.

Vestranden

The Vestranden gneiss area is lithologically much more complex than the Grong-Olden Culmination. Gneissic rocks of granitic, granodioritic and tonalitic compositions predominate. These rocks are to a large extent migmatitic. Particularly in the coastal districts, pegmatites cutting most structures are common. Basic rocks and augen gneisses of various types and origin occur in many places. Amphibolites, calc-silicate rocks, mica schists, marbles and quartz-feldspathic gneisses form cover units which are tightly infolded into the underlying basement.

These supracrustal rocks can at least partly be correlated with the rocks in the Gula Nappe occurring in the Trondheim Nappe Complex (Johansson et al. 1986 a). In the coastal districts, basement gneisses form culminations separated by deeply downfolded supracrustal rocks of unknown age (Ramberg 1944, Krill 1980, Schouenborg 1986, Möller 1986). Less deformed basement rocks with preserved older structures occur in kilometer-wide, lens-shaped areas surrounded by intensely sheared gneisses (Johansson, paper VII this volume). Ramberg (1966) described overturned and inverted anticlines of basement gneisses. Another important structural feature of the Vestranden area is the prominent N-E to ENE trending extension lineation which occurs especially in the southern part of the area. Ramberg (1977) suggested that this lineation could indicate a different direction of Caledonian nappe translation than that in the eastern Caledonides where an E-W lineation indicates the direction of translation. Roberts (1983) suggested that the Vestranden lineation is a younger structure developed during a Devonian compressional phase.

In contrast to the Grong-Olden Culmination, the Vestranden area has undergone several stages of deformation and metamorphism. Radiometric datings, carried out by the Dept. of Geology in Lund in cooperation with Naturhistoriska Riksmuseet in Stockholm, clearly show that the tonalites and granites were to a large extent formed between 1750 and 1830 Ma ago. Precambrian high grade metamorphism is also likely to have occurred around 1650 Ma. Caledonian igneous activity was restricted to the formation of approximately 400 Ma old pegmatites which intrude the coastal gneisses. Peak metamorphism in the central and eastern parts of the Vestranden region was in the amphibolite facies, locally reaching granulite facies conditions in the westernmost districts. Johansson & Möller (1986) reported temperatures and pressures around 850 °C and 15 kbar in the Roan district (Fig. 3). Larger areas, now containing rocks of the amphibolite facies, may have undergone upper amphibolite or granulite facies metamorphism, but due to the intense late retrogression, high-grade mineral assemblages are rarely preserved. Kyanite is the most widespread Al-silicate but has commonly been replaced by sillimanite (Johansson & Möller 1986) and rarely by andalusite (Johansson in prep.).

The Lurudal-Sandöla transition zone.

The Lurudal-Sandöla zone between the Luru and Sandöla rivers, (Fig. 3, 7), is a critical zone in the interpretation of the basement geology of the central Scandinavian Caledonides. It is the boundary zone between the two lithologically and tectonically contrasting basement regions, Vestranden and Grong-Olden Culmination.

The degree of exposure in the Lurudal-Sandöla area is satisfactory except in the area between Vestre and Östre Gussliklumpen, around Leirsjöen and in the northern part of the Kolåsfjell area. The scarcity of outcrops in these areas is evident from the lineament map (Fig. 6).

The tectonostratigraphy of the Lurudal-Sandöla area is shown in Fig. 8. The different nappe units can be traced from the Grong Complex, over the Grong



Fig. 6. Lineament map of the Lurudal-Sandöla area. Bold full lines are thrusts.

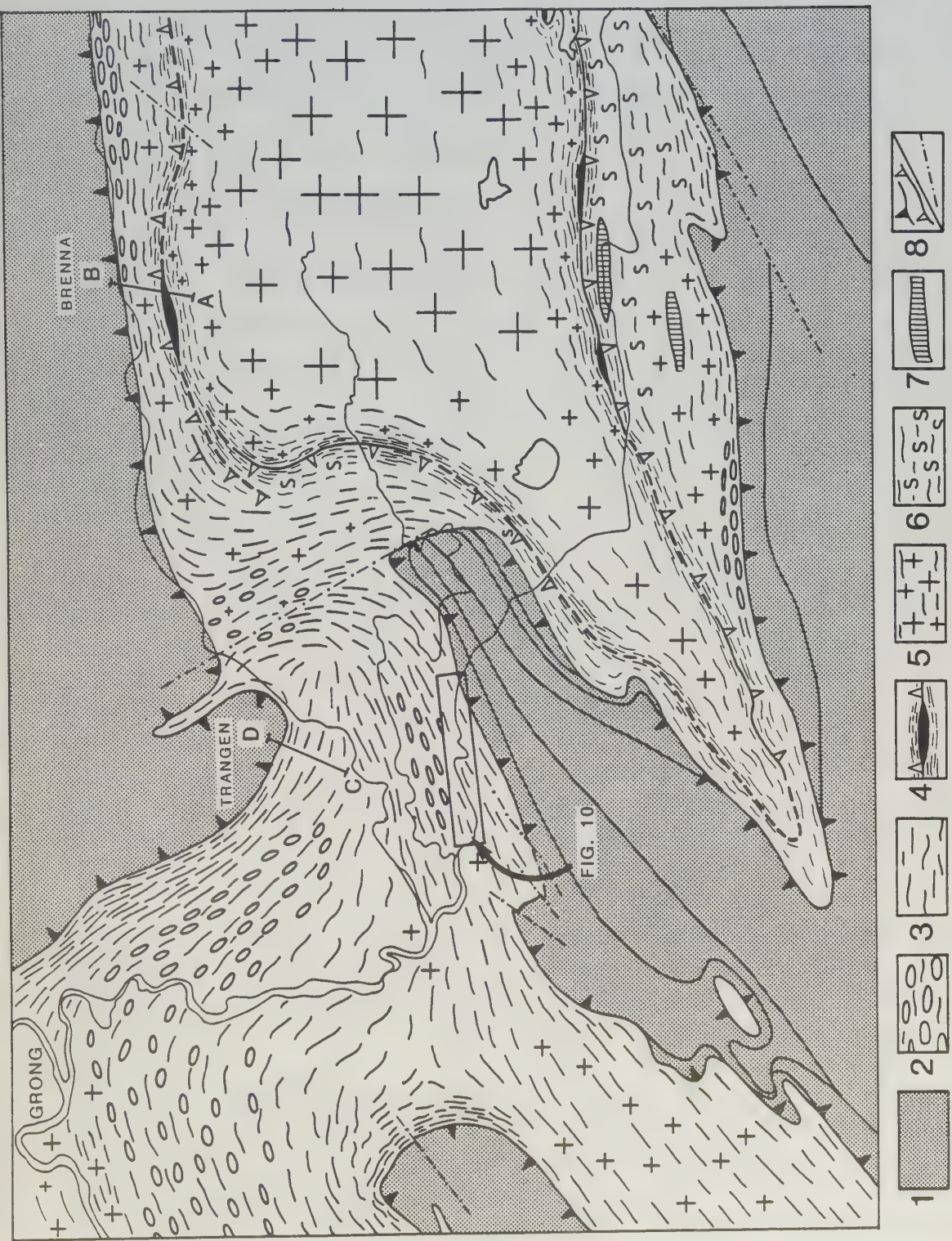


Fig. 7. Geological map of the Lurudal-Sandøla area. A-B = Brenna profile, C-D = Trangen profile. (see Fig. 9). The grain size variations in the core of the Grong Antiform are shown as "+" signs of varying size. 1 = undifferentiated Caledonian cover. 2 = augen gneisses; 3 = undifferentiated gneisses; 4 = Jämtl. Superg. meta sediments in thrust zones; 5 = granitic gneisses; 6 = paragneisses, mainly volcanic rocks; 7 = metabasites; 8 = thrusts / faults.

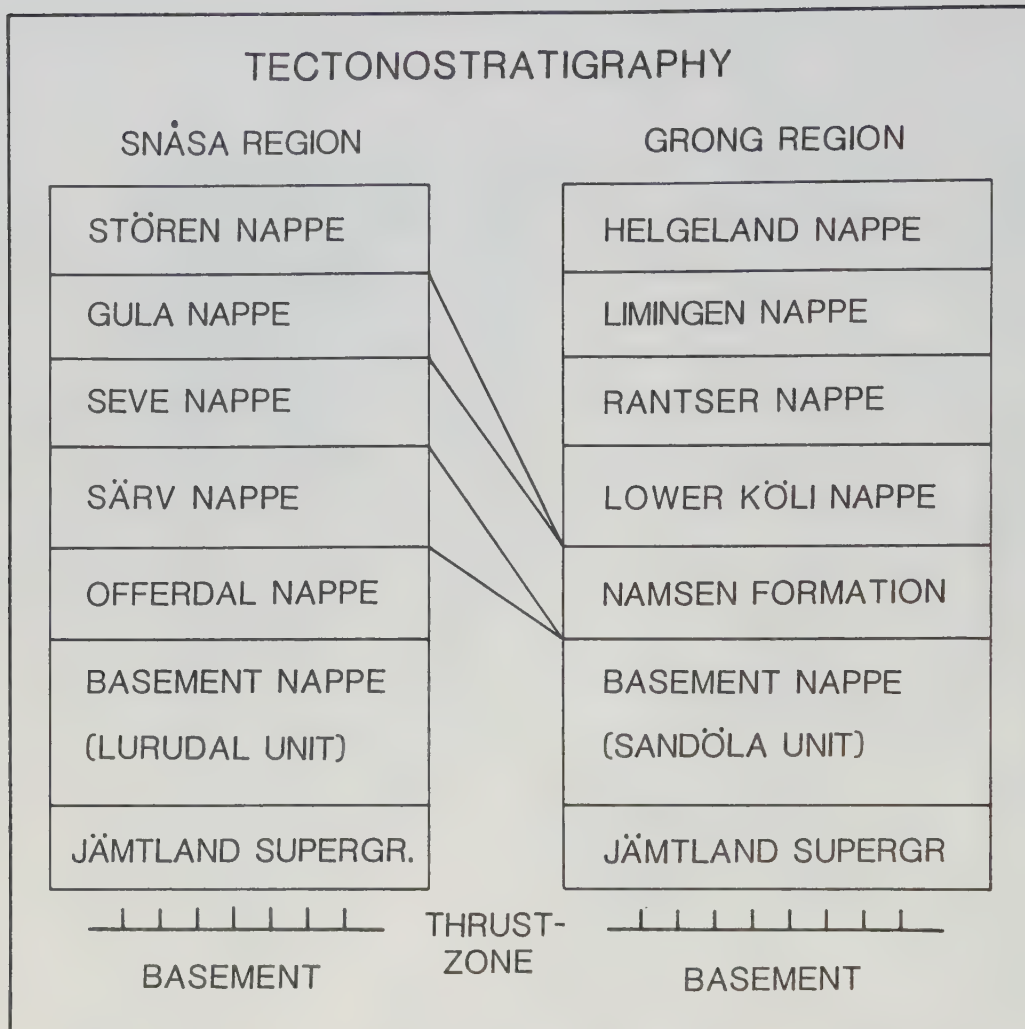


Fig. 8. Tectonostratigraphy of the northern (Grong region) and southern (Snåsa region) parts of the Lurudal-Sandöla area. All units are separated by thrust zones, but only the lowermost thrust zone is shown in the figure.

Antiform into the Snåsa Synform (Roberts 1978). The geology of the different Caledonian nappes above the Basement Nappe are treated in papers by Kollung (1979; the Grong Complex) and Andreasson and Johansson (1982; the Snåsa Synform) and is therefore not considered further here.

Basement lithologies beneath the thrust zone - The core of the Grong Antiform is structurally the deepest unit in the Lurudal-Sandöla area. It consists almost exclusively of granite. A ten kilometre long profile northwards from Dalvatnet (Fig.3) revealed nothing but granite of varying degrees of deformation and occasional metabasites. The basement granite is a medium to coarse-grained reddish rock consisting of microcline, plagioclase, quartz, and biotite. Apatite,

zircon and opaques are accessory phases. Subordinate amounts of fine-grained granite occur locally. Hornblende, garnet, epidote and phengitic white mica are typical metamorphic minerals found in the granite. Toward the thrust zones, the grain size is strongly reduced and the granite is intensely sheared. The metabasites are also intensely deformed and the original igneous mineralogy is completely replaced by hornblende, plagioclase, quartz, biotite, epidote, garnet, sphene, chlorite, and opaques.

Lithologies in the thrust zone - Thrusting is not restricted to a single zone. Rather, it occurred along a number of minor shear zones. The thickness of these thrusts zones varies from a few metres to nearly 300 m. The strain was obviously very inhomogeneously distributed and comparatively well preserved rocks are interleaved with extremely sheared gneisses.

Remnants of metasediments resembling those of the Jämtland Supergroup occur also within the thrust zones of the Lurudal-Sandöla area (Fig. 7). Isoclinally folded bluish quartzite is found in a roadcut at Bergfossen (Fig. 3). North of Dalvatnet, a thin marble with galena and sphalerite mineralizations occurs in a thrust. The metasediments have been deformed beyond recognition of primary structures. In places where there are no intervening metasediments, the gneisses have been thrust against each other and a number of tectonical and chemical processes comprising ductile and brittle grain size reduction, nucleation, and growth of new minerals have occurred. In the Nordli area, Stel (1984) studied in detail the development of different textures and mineral reactions induced by deformation. The most important result of these processes is an increase of the content of phengitic white mica and epidote at the expense of K-feldspar and plagioclase. Andreasson (1978) and Andreasson and Lagerblad (1980) described similar alteration in rocks from the Tömmerås Window. The granitic gneisses have thereby been transformed into quartz-mica schists (phyllonites) with or without epidote. Ultramylonitic rocks, free of phyllosilicates, occur in some places. Their formation may have been controlled by deformation at lower water pressures than those prevailing during the formation of the phyllonitic thrust zones.

Lithologies above the thrust zone - The nappe thrust above the core of the Grong Antiform is lithologically complex. There is a regional pattern of the distribution of different lithologies. A large basic dyke with igneous mineralogy and ophitic texture forms the highest parts of Reinhornfjell (Fig. 3). In Lurudal, south of the Grong Antiform, comparatively well preserved volcanic rocks occur together with metabasites. These lithologies are very similar to the rhyolitic porphyries and metabasites in the Olden Antiform and in the Tömmerås Window. Pegmatites or migmatites are not found in the Basement Nappe in Lurudal. Blastomylonites and augen gneisses developed locally along the contacts against stratigraphically higher units.

In the Sandöla valley, on the northern side of the Grong Antiform, the rocks are quite different. There is a rapid lithological variation which cannot be represented on maps in ordinary scales. However, two detailed profiles (Fig. 9.) were made to the northwest (Trangen profile, A-B in Fig. 7) and the north (Brenna profile, C-D in Fig. 7) of the Grong Antiform, and a special map of the shores of the

Lurudal river was prepared (Fig. 10). The profiles were made along almost dry streams during the hot summer of 1980. The profiles are therefore detailed and almost continuous. The main lithologies were found to be red and grey fine grained gneisses, a variety of augen gneisses, granitic gneisses, amphibolites, mica schists, finely banded gneisses and quartz-feldspar gneisses. The occurrence of quartz-feldspar gneisses, mica schists and even quartzites strongly suggests a supracrustal origin of the gneisses in the upper part of the Trangen profile. Oftedahl (1964) considered the layering of these gneisses as an indication of primary sedimentary bedding.

The lithological difference between the Basement Nappe in the Sandöla and the Lurudal areas is also seen in the map by Foslie (1958). A similar situation exists along the eastern and southeastern side of the Grong Antiform, where a lower part of the overthrust Basement Nappe largely consists of metavolcanic rocks of the Olden type, whereas the upper part is composed of augen gneisses and coarse granitic rocks. In Foslie's map (1958), the upper and lower parts are separated by a mylonite zone with remnants of Jämtland Supergroup metasediments.

The Geitfjellet area - The westernmost part of the transition area is dominated by the Geitfjellet mountain (Fig. 3). Coarse grained granite grading into augen gneiss occurs on the northern slope of Geitfjellet and in the adjacent Rognsmoklumpen hill. These rocks are partly migmatitic and are intruded by mafic dykes. They are rich in xenoliths of tonalitic composition. The Geitfjellet granite forms a less than 500 m thick slice underlain by the rocks shown in the Trangen profile (Fig. 9). The age of the Geitfjell granite was determined by U-Pb zircon dating (Johansson et al. 1986 a). The granite is 1823 ± 21 Ma old. Preliminary results also indicate that the Rb-Sr system was disturbed about 1650 Ma ago.

A prominent fold structure, where a sequence of supracrustal rocks was infolded in the Geitfjellet basement gneisses, occurs in the southern part of Geitfjellet. The supracrustal sequence comprises marble, amphibolites, calc-silicate gneisses and mica schists.

Structures

Andreasson and Johansson (1982) subdivided the structural history of the Snåsa Synform into four separate phases, D1 to D4. D2 through D4 are common in the Caledonian allochthon and the basement. This designation system is retained for the deformation phases recognised in the Lurudal-Sandöla transition zone. Pre-D2 fabrics are in the following text referred to as "early fabrics". The structural history is summarized in Table 1.

Early fabrics - There exist two kinds of early fabrics: *primary* structures such as bedding, igneous textures etc. and *secondary* structures and textures formed due to pre-D2 deformation and metamorphism. Early fabrics are very sparse and sometimes not readily identified. Primary layering is seen in supracrustals in the Luruälven river gorge southeast of Dalvatnet (Fig. 11) and in an outcrop in the Medöla river. Igneous and pyroclastic textures are found in metavolcanic rocks in the area between Leirsjöen and the Medöla river. Ophitic textures and igneous

Deformation phase		Fabric	Figures
	S 0	Bedding and compositional banding in supra-crustal rocks.	Fig. 11.
D 1	S 1	Surfaces recorded in garnet cores, where they are defined by inclusion trails.	Fig. 18.
D 2	S 2	Regional pervasive foliation with concordant or small angle discordant relationships to S 0.	Fig. 13.
D 2	F 2	Tight to isoclinal folds, axial planar to S 2.	
D 3	S 3	Poorly developed axial plane cleavage in the hinge zones of F 3 folds.	
D 3	F 3	Open to close NE-SW trending folds with steep axial planes. Crenulation of S 2 surfaces. The F 3 folds become tighter westwards.	Fig. 12. Fig. 14.
D 3	L 3	Very prominent NE-SW trending lineation co-axial with the F 3 folds.	Fig. 15.
D 4	F 4	NW-SE to N-S trending largescale folds often with axial planes overturned to the west. Crenulation of S 2 surfaces.	Fig. 12. Fig. 14.
D5	S 5	Faulting planes; NE-SW and NNW-SSE trending faults.	

Table 1. Summary of the deformational history of the Lurudal-Sandöla area.

mineralogy is preserved in basic dykes at Reinhornfjell. Early foliations predating the S2 regional foliation occur as internal fabrics in garnets around which the S2 foliation is wrapped. The age of these early foliations may be either Precambrian or early Caledonian.

D-2 structures - The most important D2 structure is the regional penetrative foliation (S2) which is found virtually everywhere in the area (Fig. 12). The S2 foliation was developed during the ESE-directed major thrusting of the Caledonian allochthon. It has a concordant or low-angle relationship to the earlier structures

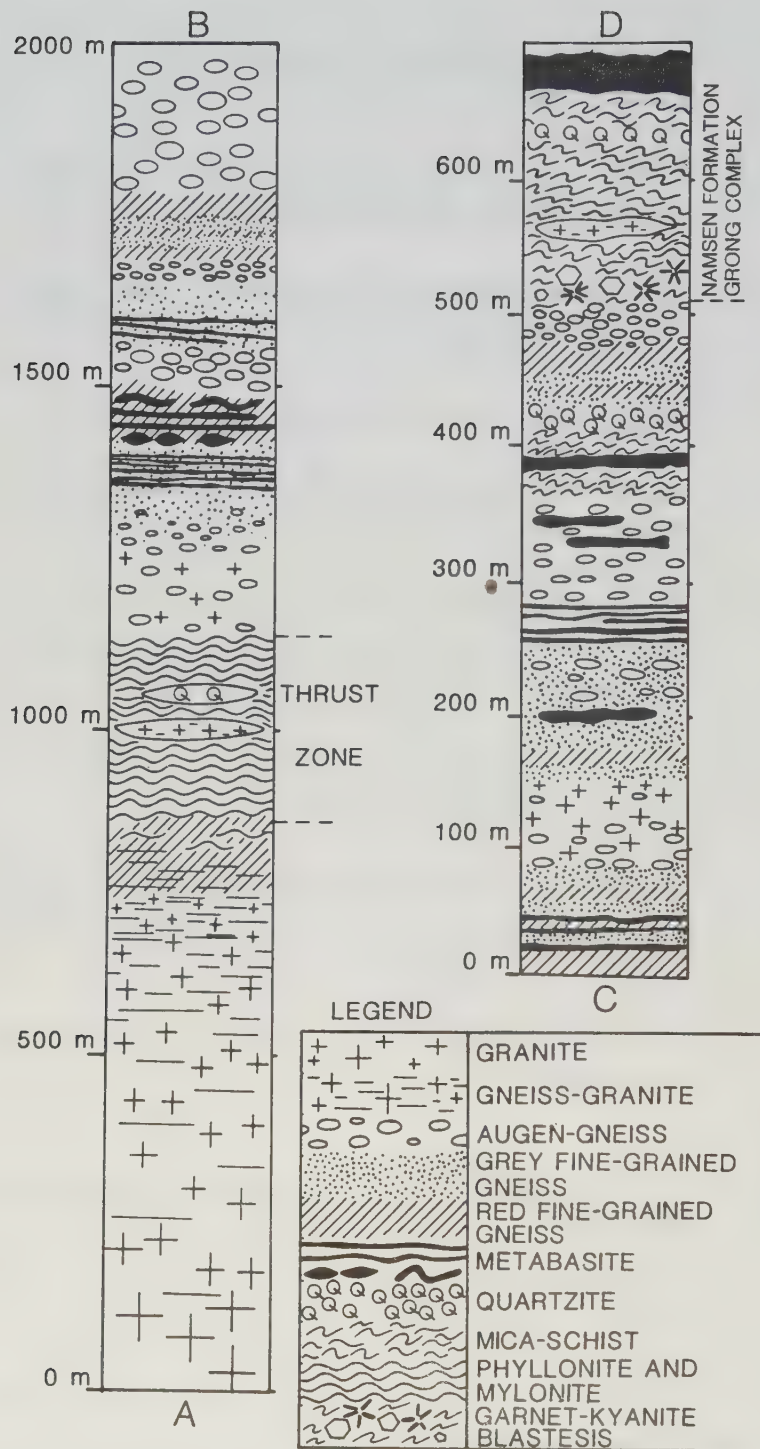


Fig. 9. Profiles showing the lithological variation in the Basement Nappe north and northwest of the Grong Antiform. A - B = Brenna profile; C - D = Trangen profile. (cf. Fig. 7.).

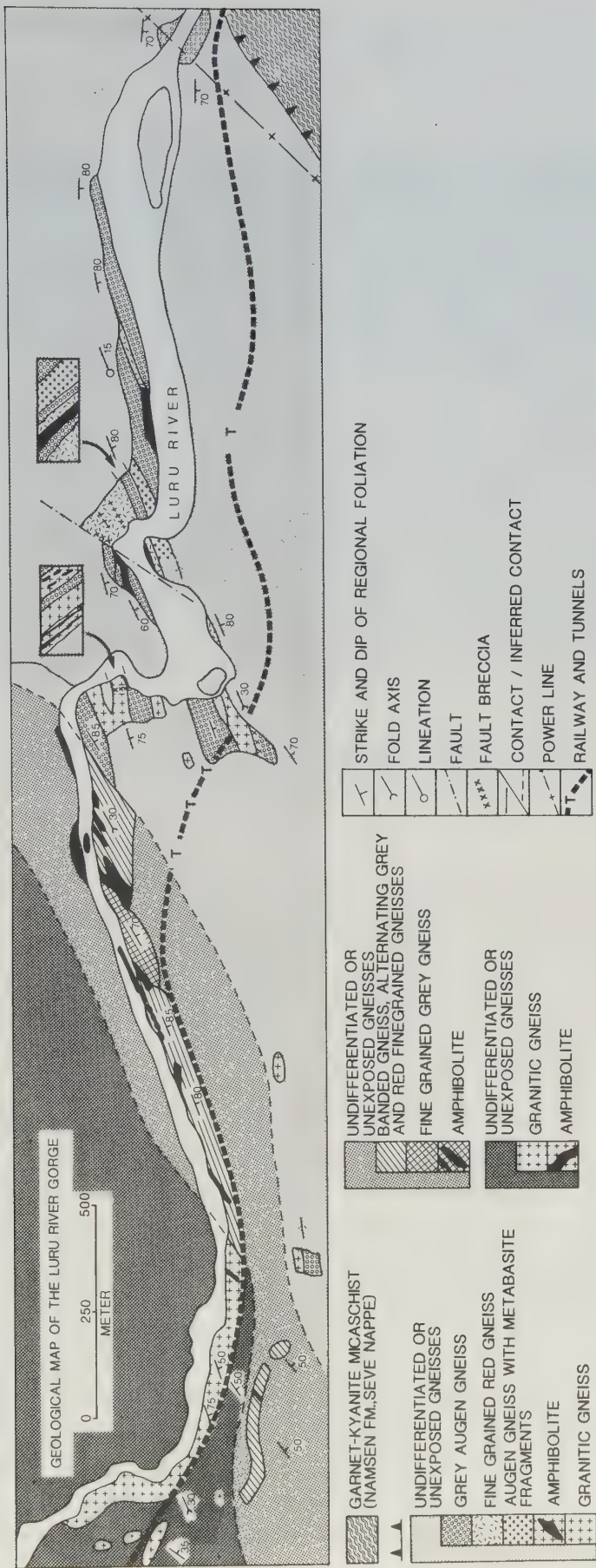


Fig. 10. Detailed geological map of the banks of Luru River. (c.f. Fig. 7)

(Fig. 13). The S₂-surfaces are defined by mica minerals which follow the axial planes of tight to isoclinal F₂ folds. These folds are frequent in thrust zones and in the quartzite lenses within the thrusts. Isoclinal F₂ folds can be seen in quartzite in the roadcut at Bergfossen (Fig. 3). Andreasson & Johansson (1982) subdivided the F₂ folds into two groups having different axial trends. The early F₂ folds have trend approximately N-S. However, during the thrusting, the F₂ fold have often been rotated into E-W trends typical of the late F₂ folds. The reorientation of linear structures into the direction of tectonic transportation is a characteristic feature in the eastern Scandinavian Caledonides (Kvale 1953, Lindström 1961, Bryant & Reed 1969, Gee 1975). Due to the strong influence of later folding, a subdivision of the F₂ folds in the basement into early and late folds is difficult in the Lurudal-Sandöla area.

D-3 structures - All major synform-antiform pairs such as the Snåsa and Flåtjern Synforms, the Kolås, Grong and Olden Antiforms, and the Tømmerås Window were formed during the D₃ event (Figs. 2, 3, 12). F₃ folds are common on all scales. Typically, they are open to close folds with steep axial planes. A weak S₃ foliation is sometimes developed around the hinges of F₃ folds. In the northwestern part of the transition area, the axial plane of F₃ folds become overturned westwards and northwestwards. The D₃ deformation also caused a crenulation of the S₂ regional foliation (Fig 14). The ENE-WSW trending extension (L₃) lineation (Fig. 15) is a very prominent fabric in large areas of Vestranden but loses much of its prominence when approaching the Grong-Olden Culmination. This lineation is coaxial with the major D₃ synforms and antiforms formed by the same event and should not be compared to the E-W trending lineations which are connected with nappe translation.

There is rapid change in style of the F₃ folds from open and gentle folds in the southeastern part of the Snåsa Synform to tight and somewhat overturned folds in the Flåtjern Synform. Farther west, on Geitfjellet, the cover and basement are isoclinally infolded in overturned antiform-synform pairs. This change in style may reflect a gradual change in the physical state of the rocks when proceeding NW. This change is accompanied by an increased importance of the L₃ lineation.

D4-structures - At least three major N-S and NNW-SSE trending D₄ fold structures occur in the Grong-Olden Culmination. The largest one is the Nordli Antiform (Fig. 2, 3, 12). In the Lurudal-Sandöla area, megascale F₄ folds refold the D₃ structures at Trangen (Fig. 2). The Trangen folds are overturned toward the west and it is possible that the D₄ deformation is also responsible for the refolding and westerly overturning of the axial-plane of Flåtjern D₃ Synform and the thrust zone ESE of Vestre Gussliklumpen. D₄ folding also caused a crenulation of the S₂ foliation and crossfolding of the F₃ crenulation. The two sets of crenulations are easily seen in mica-rich layers in the most schistose rocks of the thrust zone (Fig.14).

D5-structures - This last deformation episode was mainly brittle in character. The NE-SW and NW-SE trending faults have been active at least since the early Devonian. Faults trending NE-SW delimit the Devonian basins and can be traced into the Snåsa-Grong region. In the Lurudal-Sandöla area, several such faults occur. Most of the faults do not influence the tectonostratigraphy significantly; however,

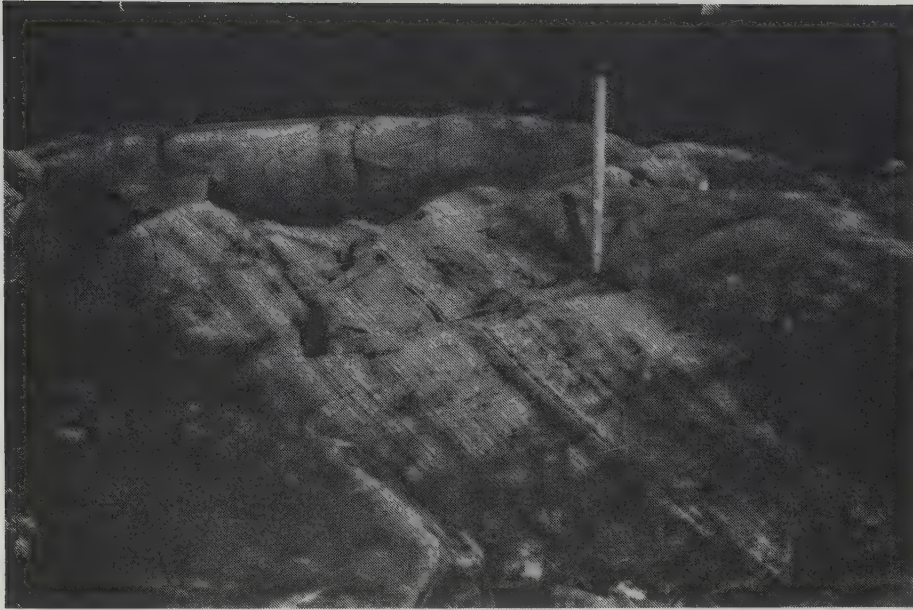


Fig. 11. Primary compositional layering (bedding) in a supracrustal rock on a small island in the Luru river 400 m southeast of Dalvatnet. The length of the hammer is 60 cm.

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where there are displacements, the shift is generally sinistral. The influence of faulting is best seen at Reinhornfjell where Foslie's map (1958) shows a displacement by 3 km of the contacts between the Basement Nappe and the Seve Nappe. At Bergfossen (Fig. 3), the northern margin of Grong-Olden Culmination has been sinistrally displaced. At Heia, a fault breccia exceeding 200 m in thickness occurs in a road cut. Minor faults often associated with breccias are very common especially in the area between Sandöla river and the Flåtjern Synform (Fig. 2). These breccias are usually cemented by calcite and quartz. Minor occurrences of chlorite, epidote and stilbite suggest cementation at low-grade metamorphic conditions.

Lineaments - A compilation of the lineaments in the Lurudal-Sandöla area is shown in Fig. 6 . The lineament map is based on a study of black and white aerial photographs on a scale of approximately 1:35000. There is very good correlation between the lineaments and the regional foliation (Fig. 6, 12). The large-scale structures such as the curvature of the thrust zone between the core of the Grong Antiform and the Basement Nappe is easily seen in the lineament pattern.

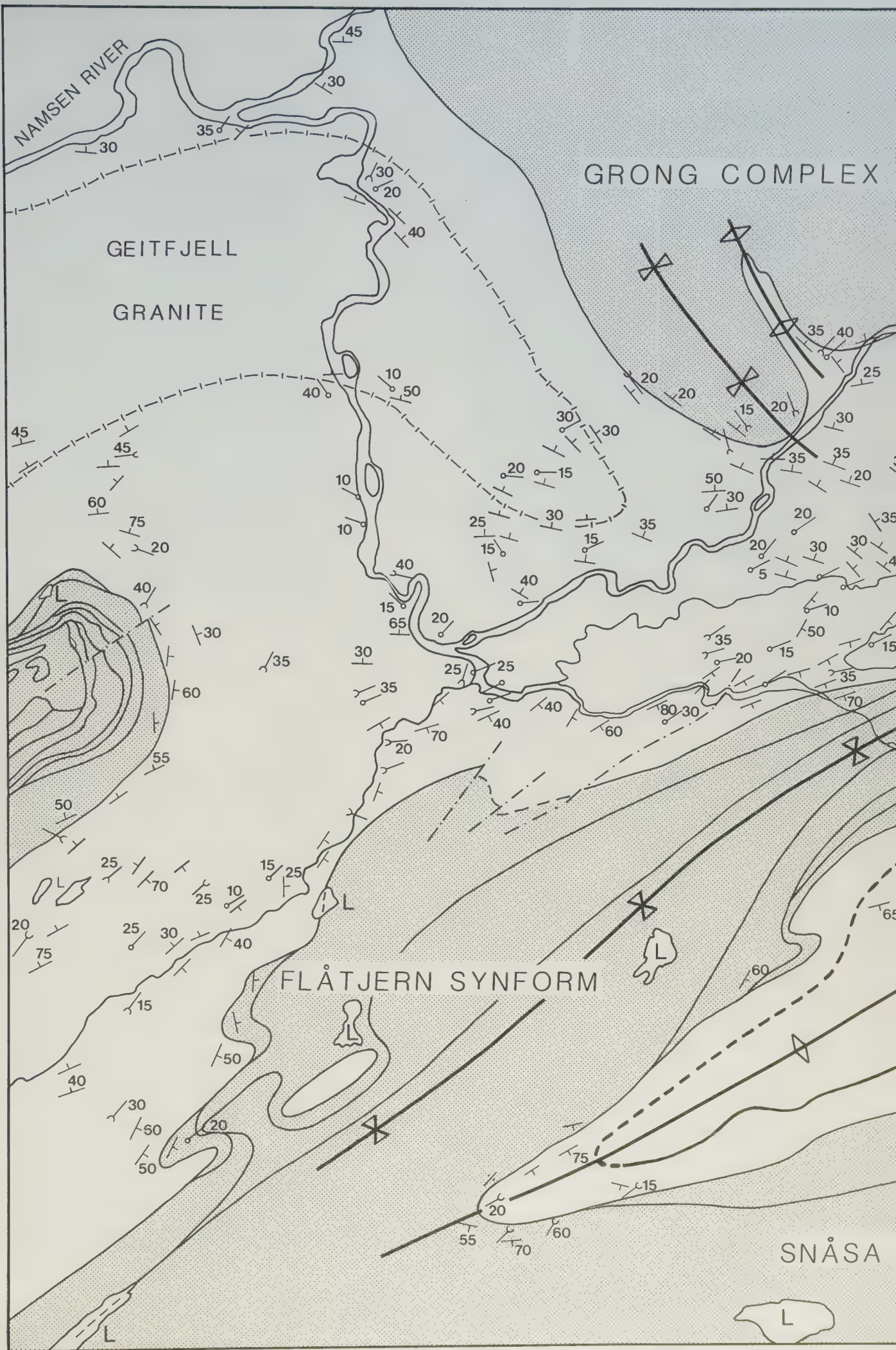
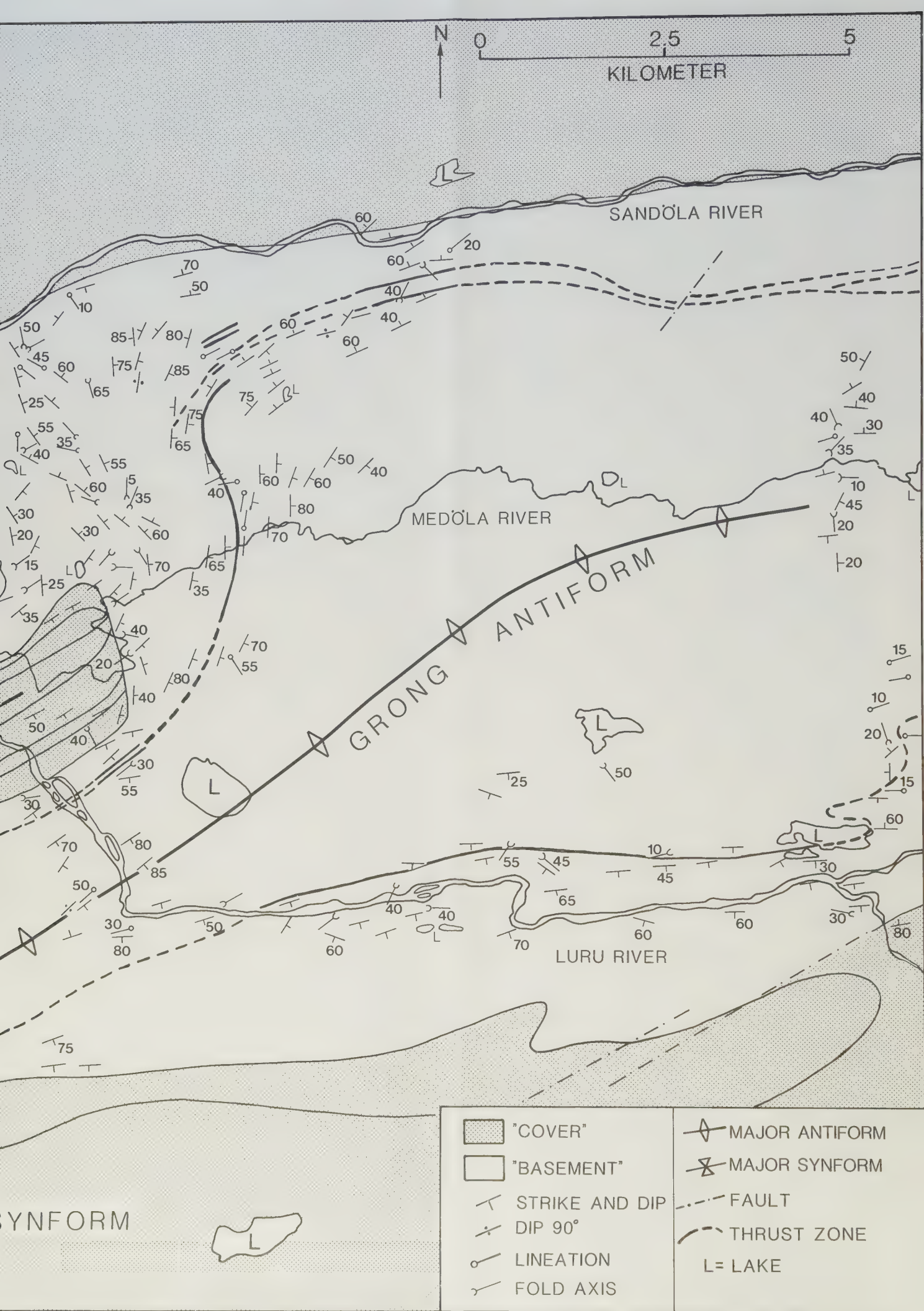


Fig. 12. Map showing representative strikes and dips of the regional foliation.



n (D2), lineations and fold axes in the Lurudal - Sandöla area.

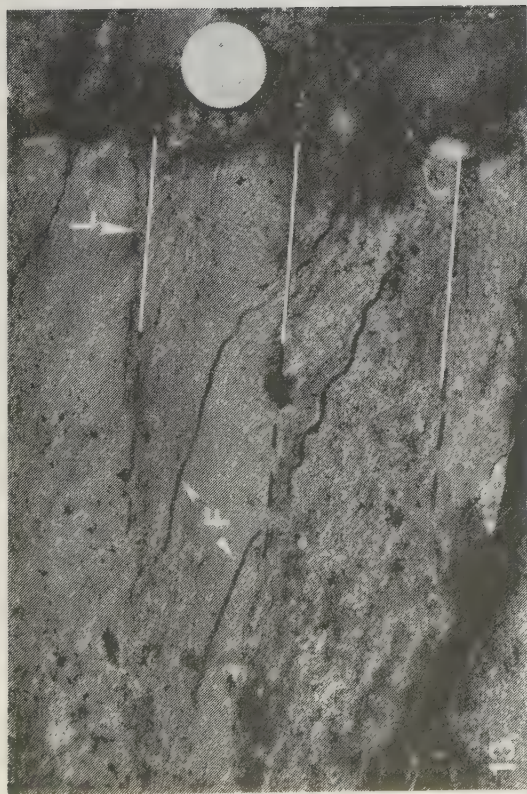


Fig. 13. Primary compositional layering (L) cut by D2 regional foliation (F) in an exposure in the Medöla river (Fig. 3.). In the layer to the left of the coin, the grain size is coarser in the upper part of the layer and the cleavage is refracted. The diameter of the coin is 25 mm.



Fig. 14. Two nearly perpendicular sets of D3 and D4 (?) crenulations in mica schist along the Medöla river. The two sets are shown as white lines in the upper part of the photo. The length of the match is 50 mm.



Fig. 15. Extension lineation (L3) in granitic gneiss in the Holden area (Fig. 2). Length of the scale is 12 cm.

Metamorphism

The little deformed basement lithologies of the Grong-Olden Culmination are not very suitable for metamorphic studies. This is due to the predominance of granites and acid volcanics. Metamorphism in the Lurudal-Sandöla area is therefore studied best in thrust zones. In their intensely deformed, rocks the thrust-related main foliation (S2) can easily be recognized. Mineral growth in relation to this marker foliation is readily observed. Growth of new minerals was also enhanced by grain size reduction, increased element mobility and the circulation of fluids in the thrust zones. The occurrence of metasediments and the tectonic mixing of different rocks gave the rocks of the thrust zones more varied compositions than those of the less deformed basement. Nevertheless, index minerals are few even in the thrust zones, and more than two index minerals can seldom be observed in a single thin section. Minerals that grew before or in the early stage of the thrusting occur as remnants in the S2 foliation. Due to the D2 deformation these minerals have lost their original growth relationships. In this case it is difficult to define parageneses of index minerals with mutual grain boundaries. As a mean of tectonic analysis, the minerals found in the thrust zone are therefore grouped (Fig. 16) on the basis of their relationship to the main foliation (S2). Also the minerals that grew during the late stage brittle deformation are included in Fig. 16.

In thin sections it is impossible to separate between D3- and D4-phase mineral growth because both events caused similar crenulations of the S2 foliation.

The highest metamorphic grade which was in the middle amphibolite facies, is indicated by the presence of staurolite, kyanite, garnet and hornblende. Staurolite and kyanite have only been found in the thrust zone south of Brenna (Figs. 7, 9). The staurolite, kyanite (Fig. 17) and some garnets (Fig. 18) *predate* the S2 foliation. In comparison to kyanite and staurolite, garnet is a common mineral in the thrust zones of the Grong Antiform. There exist at least three generations of garnets, pre-, syn- and post-dating the S2 foliation, respectively. It is obvious that the compositions of the various garnets were strongly influenced by the bulk composition of the rocks in which they occur. Garnets with 35 to 38 % spessartine component are found in syntectonic garnet bands north of Leirsjöen. West of Gussliklumpen, in contrast, garnet with no spessartine and more than 40 % grossular component occurs syntectonically in plagioclase rich gneisses. All the garnets are rich in almandine (55 - 75 %) and poor in pyrope (< 10 %). Due to the generally high contents of manganese and calcium these garnets are poorly suited for precise garnet-biotite thermometry. Some representative garnet compositions are given in Fig. 19.

The reactions that formed early staurolite, garnet and kyanite are difficult to deduce since the mineralogy and textures have been altered completely by later tectonometamorphism. Staurolite, kyanite, and garnet is also found in thrust zones in the Tömmerås Window (Andreasson and Lagerblad 1980) to the south of the Grong Antiform where the minerals formed by Caledonian metamorphism (syn- to postkinematic). In the basal parts of the Tömmerås Window, Andreasson and Lagerblad (1980) estimated that peak metamorphism occurred at 550 °C and 6 - 8 kbar. Similar conditions probably also existed in the Lurudal-Sandöla area.

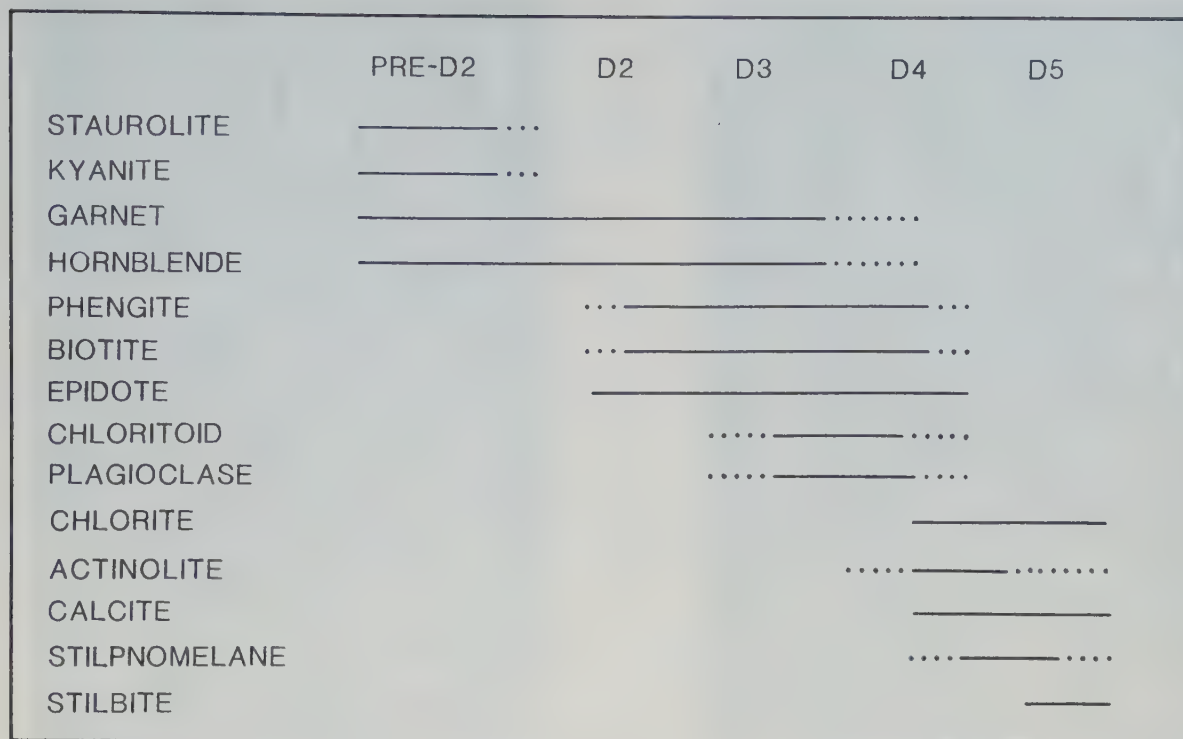


Fig. 16. The growth of different metamorphic minerals in relation to the deformation events in the Lurudal-Sandøla area.

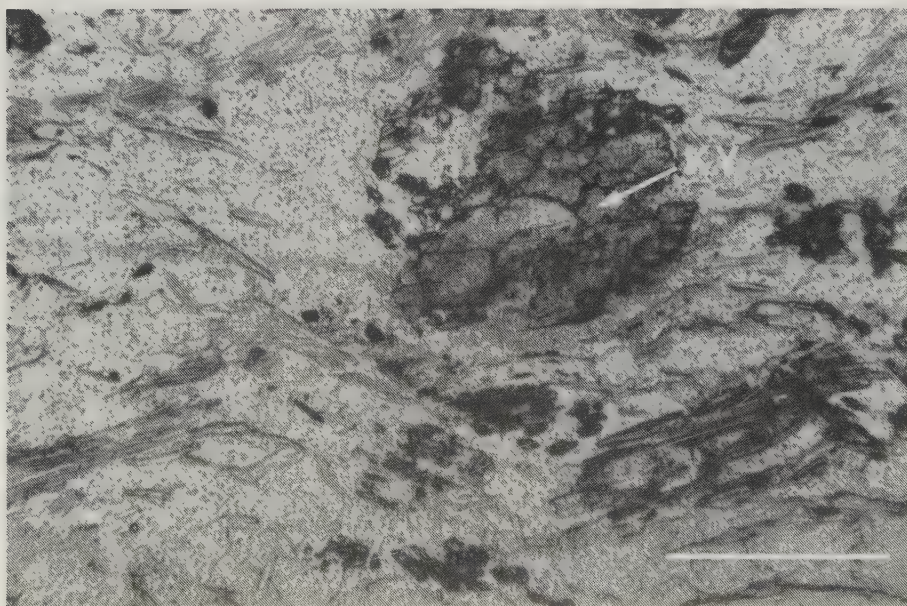


Fig. 17. Kyanite predating the D2 regional foliation defined by mica flakes. The length of the scale bar is 3 mm.

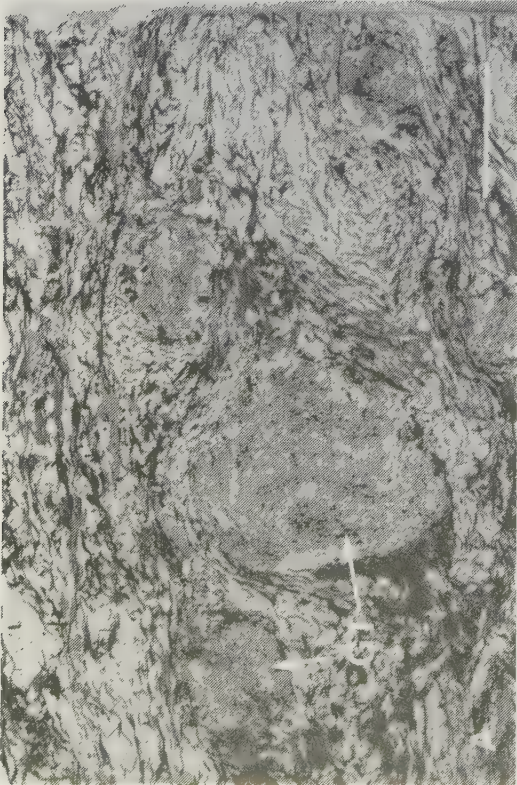
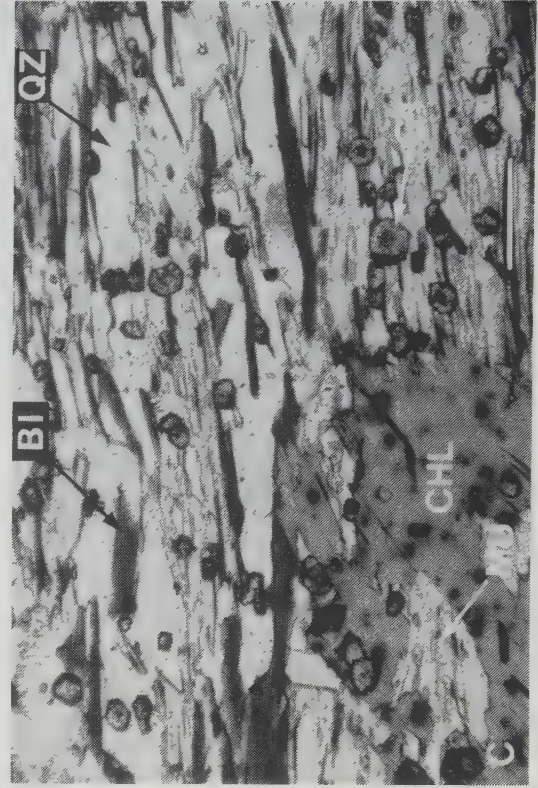
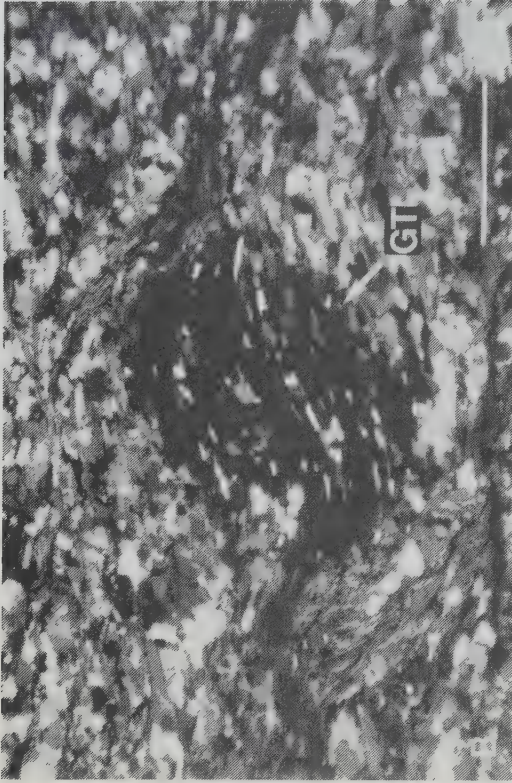


Fig. 18. Garnets pre- (A), syn- (B), and post-dating (C) the D2 regional foliation. The garnets were found in the thrustzone beneath the Basement Nappe. The samples derive from west of Dalvatnet (pre.-D2 garnet), Gressåmoen (syn.-D2 garnet) and northwest of Leirsjøen (post -D2 garnet). For locations see Fig. 3. The length of scale bars are: (A): 6mm, (B): 4 mm, (C): 3 mm. GT = garnet, BI = biotite, QZ = quartz, MU = muscovite, CHL = chlorite.

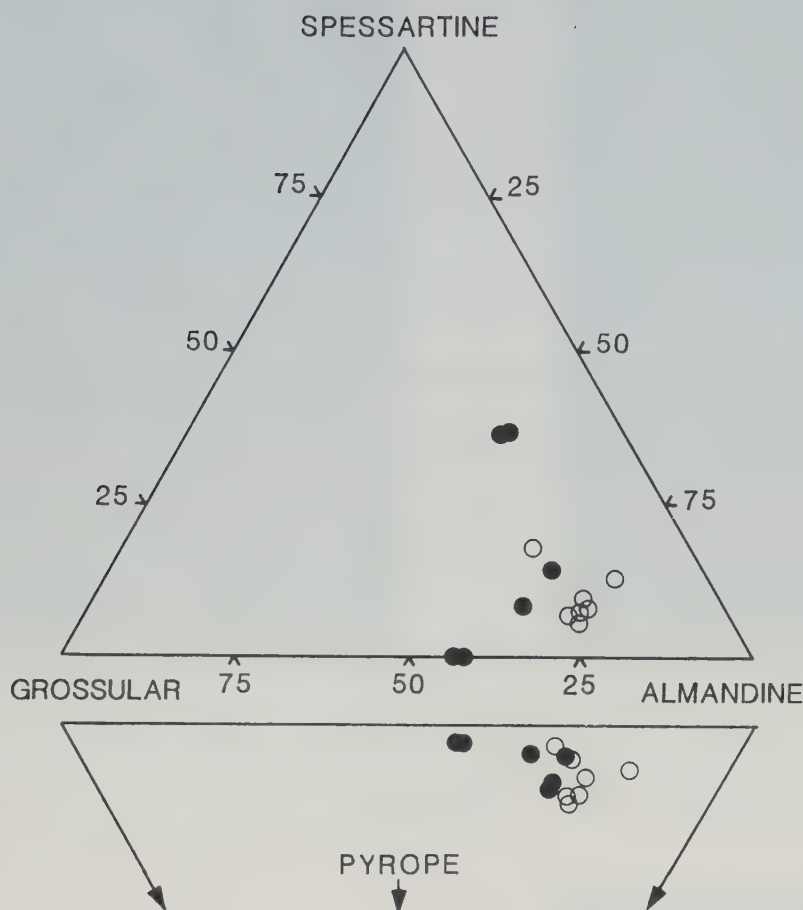


Fig. 19. Triangle diagram showing some representative garnet compositions in terms of garnet end-members. Filled and open circles denote garnets growing syn- and posttectonically respectively, in relation to the D 2 regional foliation.

The metamorphic conditions during the formation of the S2 foliation are characterised by the stability of phengitic white mica, biotite, quartz, epidote, hornblende, garnet, and ilmenite.

Metamorphism, partly retrogressive and postdating the S2 foliation was extensive in the Lurudal-Sandöla area. Chloritoid (Fig. 20), biotite (Fig. 21), plagioclase, garnet (Fig. 18), actinolite (Fig. 22) and chlorite overgrew this foliation. Together with calcite, stilpnomelane and stilbite, these minerals reflect a decrease of the pressure and temperature from the middle amphibolite facies through greenschist to zeolite-facies conditions. Chloritoid occurs only in the staurolite-bearing sample where it may replace staurolite. Chlorite replaced chloritoid, garnet and biotite. Together with actinolite, chlorite represents

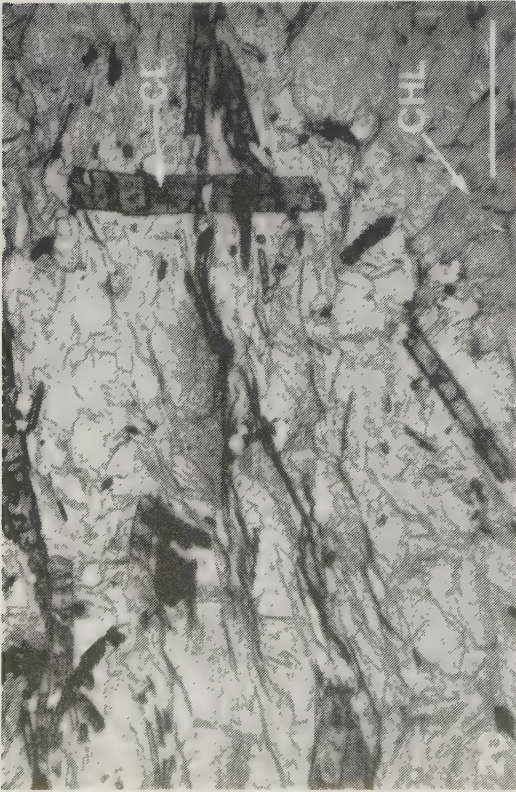


Fig. 20. Randomly growing chloritoid postdating the D2 regional foliation. The length of the scale bar is 2 mm. CL = chloritoid, CHL = chlorite.

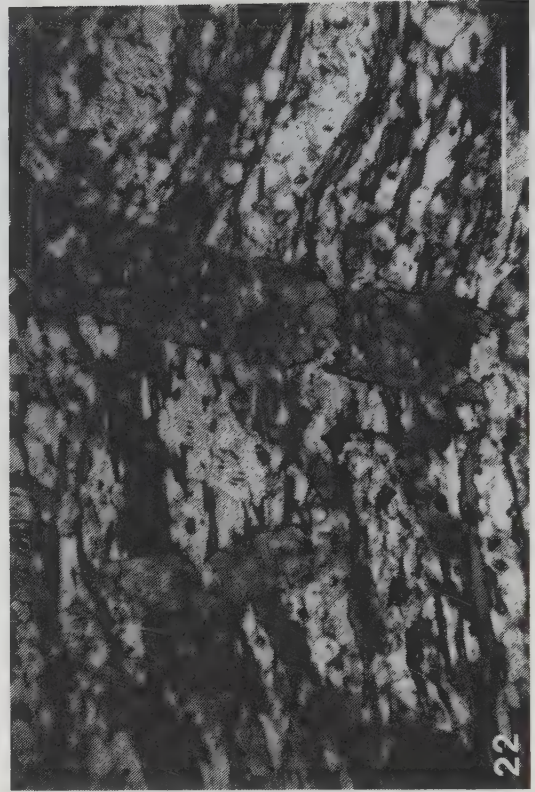


Fig. 21. Biotite porphyroblast with inclusion trails defining the D2 regional foliation. The length of the scale bar is 3 mm.

Fig. 22. Actinolite growing across the D2 regional foliation. The foliation is defined by chloritized biotite. The length of the scale bar is 2 mm.

greenschist facies conditions. Stilpnomelane grew as small randomly oriented rosettes in intermediate to basic rocks. The last phase of mineral formation represents zeolite facies conditions. It is recorded in many fault breccias which are cemented by stilbite, calcite and quartz grown in open cavities.

Discussion

As shown in the preceeding chapters there are several geological differences between the western and eastern basement regions. Some of them are clearly of Caledonian age, whereas others developed in the Precambrian. It is therefore of interest to discuss not only the Caledonian relationships but also some of the pre-Caledonian aspects.

The relationship between the Grong-Olden Culmination and the Vestranden region - The tracing of the basal thrust zones along the margin of the Grong Antiform confirmed the correctness of Foslie's mapping (1958, 1959, 1960) also disclosing some new occurrences of metasediments of the Jämtland Supergroup. A most important finding is that the thrusts can be followed into the Kolåsfjell area (Fig. 2, 7). This implies that the thrust planes pass beneath the Flåtjern Synform and an overthrust part of the Vestranden basement. Due to the lack of exposures it is not possible to continuously follow the northern thrust zone around the innermost part of the Kolåsfjell basement area and connect it to the southern thrust zone in the Kolåsfjell area. There exists, consequently a clear tectonic relationship between the core of the Grong-Olden Culmination and the Vestranden area. This also requires the assumption of crustal shortening in the Lurudal-Sandöla area. The highest metamorphic grade predates the thrust foliations. If this metamorphism is of Caledonian origin, as appears probable, (paper II-24) there also exist a tectonic disturbance of the regional metamorphic patterns.

The occurrence of typical Olden Window lithologies, i.e. rhyolites and basic dykes with well preserved igneous mineralogies, in the Basement Nappe at Reinhornfjell and in the nappe thrust over the core of the Tömmerås Window is another indication that the Grong-Olden type lithologies plunge down beneath an overthrust part of Vestranden. No rhyolites of the Olden Window type have so far been found west of Lake Snåsavatnet among the migmatitic Vestranden gneisses. If the Olden rhyolites have been reworked beyond recognition in the Vestranden area, this would imply an enormous increase of Caledonian deformation and metamorphism over a short distance. This is very unlikely because well preserved Caledonian cover units occur in this area (Andreasson & Johansson 1982, Johansson et al. 1986 a).

The occurrences of allochthonous, lithologically distinct Olden-type rocks in the Tömmerås Window and at Reinhornfjell can be explained if these have been derived from areas now overthrust by Vestranden gneisses. The field relationships in the Lurudal-Sandöla area, in Gressåmoen, in the eastern part of the Grong Antiform, and in many other places show that the Grong-Olden Culmination basement is imbricated with slices of basement rocks alternating with minor thrust zones with or without metasedimentary rocks. A similar situation can

be seen in the Tömmerås Window.

The occurrence of Jämtland Supergroup metasediments in the thrust zones, the development of secondary tectonic concordance or near concordance between the different nappe units, the trends of the lineaments, and the Caledonian mineral ages unambiguously relate the major deformation, thrusting and metamorphism in the Lurudal-Sandöla area to the Caledonian orogeny.

On the basis of an eight-point Rb-Sr whole-rock dating which yielded an age of 1653 ± 84 Ma for the gneisses and mylonites underlying the Namsen formation at Trangen (Fig. 9), Råheim et al. (1979) assumed that this age represented the main metamorphism and associated development of penetrative structures (D2 of this paper) in the gneissic rocks occurring allochthonously above the core of the Grong Antiform. Data from four mylonite samples regressed alone yielded an age of 1688 ± 162 Ma with a very high quality-of-fit number (QFN = 33.81). As a consequence, they also concluded that the mylonitic contact between the gneisses of the Basement Nappe of the present paper and the Namsen formation developed as a result of Precambrian thrusting. In the light of the present study, these views appear untenable. They must be rejected because of the existence of Palaeozoic metasediments in the basal thrust zone of the Basement Nappe. Furthermore structural concordance extends throughout the tectonostratigraphic sequence from the core of the Grong Antiform through the Basement Nappe upwards into the cover rocks of the Namsen formation, Snåsa Synform and Grong Complex. Throughout this sequence, the D 2 minerals and textural relationships are similar and were formed by a Caledonian event. The characteristic garnet-kyanite mica schist of the Namsen formation can without difficulty be traced into the Snåsa Synform where it forms part of the Caledonian Seve Nappe (Andreasson & Johansson 1982). The Seve Nappe is underlain by the typical 650 Ma old (Claesson & Roddick 1983) metasediment-dolerite association of the Särvi Nappe. This provides additional decisive evidence against a Precambrian age of the mylonites beneath the Namsen formation. The majority of structures in the Lurudal-Sandöla area is thus undoubtedly of Caledonian age.

The more detailed timing of the thrusting and subsequent deformation is largely unknown. However, available age data combined with studies of metamorphism give some information about the timing of the tectonothermal evolution. If the age of the phengites in the Basement Nappe in the Nordli area (Fig. 3), which define the D2 regional foliation is interpreted as a cooling age, the rocks cooled through the K/Ar blocking temperature of 350 ± 50 °C (Jäger 1979) around 430 Ma (Reymer 1979). In the Lurudal-Sandöla area, tectonically equivalent phengites were overgrown by chloritoid suggesting temperatures above approximately 500 °C (Ganguly 1969) after D2. The uranium mineralizations in the Olden Window were formed during metamorphism and brittle deformation about 420 Ma ago (Stuckless et al. 1984). Assuming that these datings are correct and allowing sufficient time for the heating and subsequent cooling of the basement to blocking temperatures, it is possible that the major deformation and metamorphism within the basement commenced in or before the middle Ordovician. Dallmeyer & Gee (1986) similarly suggest that high-temperature

ductile imbrication of the crystalline Baltic Shield basement and the late Proterozoic cover took place in the Early Ordovician.

How far to the east the basement was influenced by the Ordovician deformation is still an open question. Preliminary results from work in progress (Lindqvist & Johansson 1986) suggest that significant Ordovician deformation of the basement in the Tömmerås Window and in the Grong-Olden Culmination, cannot be excluded.

Although the tectonic build up of the Vestranden region is still very poorly known there is a number of features suggesting that also the Vestranden region may be "imbricated" on a large scale. This is supported by the existence of areas in westernmost Vestranden with marked positive gravimetric and magnetic regional patterns deviating from the patterns of the eastern and northern parts of Vestranden. There are also tectonically bounded areas with rocks of a very high metamorphic facies (Möller 1986; paper VI this volume).

The spatial relationship between the Grong-Olden Culmination and the Vestranden region was not entirely the result of a late Caledonian i.e. a Late Silurian continent-continent collision. Rocks of the Caledonian nappe cover can be traced from the Grong-Olden region into the Lurudal-Sandöla area and farther west into the Vestranden region (Andreasson & Johansson 1982, Sigmond et al. 1984, Johansson et al. 1986 a) where they continue to occupy stratigraphically high positions without being squeezed in between the Grong-Olden and Vestranden basement blocks. The upper Caledonian nappes have consequently travelled across the Vestranden region onto the Grong-Olden Culmination. Furthermore, the age relationships within the Vestranden region show that the major Precambrian rock-forming events are largely similar to those in the Svecokarelian province farther east and south in Sweden. Therefore, the interpretation of Vestranden as a part of an "American plate", as proposed by Mykkeltveit et al. (1980), finds no support in the results of the present study.

Geological relationships within the Precambrian basement - The occurrence of Olden-type lithologies (the Lurudal unit) and gneisses typical of the Vestranden region (the Sandöla unit) within a single basement nappe complex indicates a close spatial relationship between their source areas. As already mentioned, the results of this study suggest that the rocks of the Transscandinavian Belt (Fig. 1) once extended much farther to the west and were overthrust by the rocks of the present Vestranden region. This inference is strengthened by the occurrence of granites, derived from areas to the west of the present Norwegian coast, in the Caledonian nappes. One instance is the Tännäs Augen Gneiss which is petrographically similar to the Rätan granite (Lundegårdh 1967, Lundqvist 1968, Gorbatshev 1972, Claesson 1980) constituting part of the Transcandinavian Belt and occurring south of the Grong-Olden Culmination (Fig.1). The age of the Tännäs augen gneiss (1685 ± 20 Ma U-Pb zircon, 1610 ± 85 Ma Rb-Sr w.r.; Claesson 1980) fits well with the ages of the granites in the Transscandinavian Belt (1790 - 1630 Ma ; Wilson et al. 1984, Patchett et al 1986). Furthermore, radiometric datings (Pidgeon & Råheim 1972, Råheim 1977, Skjerlie et al. 1978, Brueckner 1979, Lappin et al. 1979, Mearns 1984 and Tucker 1986) from the Western Gneiss Region indicate

formation of new continental crust and/or regional metamorphism in the time interval 1600 to 1775 Ma ago which also is similar to the time of formation of the Transscandinavian Belt.

It is therefore justified to assume that the Vestranden gneiss area largely is built up by Svecokarelian granites (the 1823 Ma old Geitfjell granite; Johansson et al. 1986 b) and tonalites (the 1820 Ma old Kolvereid tonalite; Schouenborg et al. in prep.) intruded by granites of the Transscandinavian Belt and other granites formed during the westward accretion of the Precambrian shield 1775 to 1600 Ma ago. Such a model fits well with the close spatial relation of the different types of basement rocks in the Basement Nappe.

The age pattern of the Western Gneiss Region *south of Trondheim* reproduces closely the chronology of the Southwest Scandinavian Orogen (Gorbatshev 1985, Bryhni et al. 1981) with the major formation of continental crust 1775 to 1550 Ma ago, followed by important igneous and metamorphic events 1500 to 1400 Ma ago (Harvey 1983), and 1250 to 850 Ma (Corfu 1980, Gebauer 1983). North of the Trondheim fjord, in the Vestranden area, the situation appears to be somewhat different. Whereas datings of the Precambrian Vestranden basement rocks yield ages between 1823 and 1630 Ma ago (Johansson et al. 1986 b and preliminary result from ongoing work), Sveconorwegian (1250 to 850 Ma) ages have not been recorded. However, in some upper Caledonian nappes derived from areas farther to the west of Vestranden, Sveconorwegian metamorphism and pegmatite intrusions are indicated by the results of Rb-Sr datings (Reymer 1979, 1982; the Seve Nappe), Krill (1983; pegmatite in the Risberget Nappe, an equivalent of the Tännäs augen gneiss mentioned above). This suggest that a region situated to the west of Vestranden had been influenced by the Sveconorwegian orogeny whereas the Vestranden region and the Grong-Olden Culmination remained essentially unaffected. Neither are there any signs of a significant event 1500 to 1400 Ma ago.

A diagnostic feature of the eastern boundary (The "Protogine zone"; Fig. 1) of the Southwest Scandinavian Orogen is an approximately 900 to 1000 Ma old swarm of mafic dykes parallelling this tectonic zone. Mafic dykes of similar type have so far not been identified in the Vestranden basement, the Basement Nappe overlying the Grong-Olden Culmination or in the Grong-Olden Culmination proper. However they may well be present among the thousands of dykes and dyke fragments occurring in the eclogite and granulite terrains in the Western Gneiss Region farther south in Norway (Fig.1). The "Protogine zone" disappears beneath the Caledonian front in southeastern Norway and it is therefore uncertain whether it trends northwards towards the Grong-Olden-Vestranden region or northwestwards to the Western Gneiss Region. On the basis of observations of Sveconorwegian ages in the Seve Nappe, Reymer (1982) drew its continuation to the southwest of the Vestranden region. The results of the present work in general lend support to such an interpretation (Fig. 1).

Conclusions

The present study of the Grong-Olden-Vestranden region allows the following conclusions:

1. Large differences with regard to lithology, metamorphism, and degree and complexity of deformation exist between the Vestranden region and the Grong-Olden Culmination. The rocks of the Vestranden region are also partly older than the granites, volcanics and mafic hypabyssals of the Grong-Olden Culmination.
2. Caledonian thrust zones with remnants of metasediments belonging to the Late Proterozoic - Palaeozoic Jämtland Supergroup separate the core of the Grong-Olden Culmination from an overthrust basement nappe complex (the Basement Nappe). The latter comprises a lower unit of rocks typical of the Grong-Olden basement and an upper unit composed of rocks comparable to those occurring in Vestranden. The occurrence of Jämtland Supergroup metasediments in thrust zones demonstrates that these thrusts are Caledonian.
3. The rocks in the core of the Grong-Olden Culmination plunge westwards beneath the Vestranden gneisses.
4. The tectonic relationship between the Grong-Olden Culmination and Vestranden implies Caledonian shortening of the crust and tectonic disturbance of the Caledonian pre-D 2 metamorphic patterns.
5. The suggestion that Vestranden is a part of an "American plate" emplaced during the continent-continent collision stage of the Caledonian orogeny finds no support in the present study. The close spatial association of Vestranden and Grong-Olden type rocks within the same basement nappe, the presence of Svecokarelian granites and tonalites in Vestranden, and the possible occurrence of equivalents of the Transscandinavian Belt granites in the Caledonian nappes are features all suggesting that the Precambrian evolution of the Vestranden region is closely tied to the Precambrian orogenic development of the Baltic Shield.
6. The Vestranden region is essentially a segment of the Baltic Shield built up largely by Svecokarelian rocks reworked and metamorphosed during the formation of the Transscandinavian Belt. Sveconorwegian ages have not been recorded in the Vestranden basement but occur in nappe units derived from areas farther west. This indicates that the front of strong Sveconorwegian reworking lies to the west of the Vestranden area.

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PAPER III

THE SNÅSA MEGA-LENS, WEST CENTRAL SCANDINAVIAN
CALEDONIDES.

Per-Gunnar Andreasson and Leif Johansson

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PAPER IV

CORRELATION OF PROTEROZOIC ROCKS ACROSS THE TRANS-SCANDINAVIAN BELT: THE GEITFJELLET GRANITE IN VESTRANDEN, NORWAY, AN EQUIVALENT OF THE SVECOKARELIAN REVSUND GRANITE IN SWEDEN.

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Abstract.

The Geitfjellet granite is a coarse-grained grey rock outcropping in the Vestranden basement south of Grong, central Norway. The Vestranden region is the northernmost part of the Western Gneiss Region in Norway. An U-Pb zircon dating of the Geitfjellet granite yield an age of 1823 ± 21 Ma. Most zircons show a compositional zoning concordant to the crystal growth planes. Other zircons have outer shells which are discordant to the crystal planes of the internal part of the zircons. Abrasion of the zircons results in somewhat higher ages suggesting an age difference between the internal part of the zircons and the outer discordant shells. The age is therefore interpreted as a minimum age of the intrusion of the granite. Rb-Sr data indicates an age of 1784 ± 11 Ma for the Geitfjellet granite.

The petrography, chemistry, isotope geology and the age of the Geitfjellet granite is similar to the 1770 - 1790 Ma old granites of the Revsund type intruding marine metasediments in the Svecokarelian Bothnian basin in central northern Sweden. A correlation of these granites is suggested. The dating of the Geitfjellet granite and of other granitoids in Vestranden, the correlation of the Geitfjellet granite and Revsund granites and the occurrence of Precambrian supracrustal rocks in Vestranden suggest that Vestranden at least partly may be a westerly continuation of the Svecokarelian Bothnian basin.

Introduction.

In western and northern Scandinavia, all Precambrian crustal segments of the Baltic Shield such as the Archean domain, the Svecokarelian-Svecofennian region, the Transscandinavian Granite Porphyry Belt and the Southwest Scandinavian Orogen (Fig.1) are partly overlain by Caledonian nappes. The western part of these regions have also been more or less reworked by the Caledonian tectonothermal event. The reconstruction of the western continuations of these Precambrian regions must therefore be based on work in the basement windows in the Caledonides, in the western coastal regions of Norway, and on studies of far-travelled Caledonian nappes which commonly contain slices of Precambrian rocks.

The Precambrian basement of the Scandinavian Caledonides is exposed in many windows along the mountain chain. In the central Caledonides, the basement

lithologies are best studied in the Western Gneiss Region, the Grong-Olden Culmination, the Børgefjell Window and the Tömmerrås Window (Fig.1). In the Grong-Olden Culmination and in its western continuation, the Vestranden area, the Precambrian basement is continuously exposed over a distance of nearly 200 kilometres across the strike of the Caledonian orogen. As regards to lithologies, deformation, metamorphism and age relationships this basement area can be subdivided into an eastern (Grong-Olden Culmination) and a western part, (Vestranden) (Johansson 1986). The eastern part, is much less affected by the Caledonian orogeny as compared to the western part.

Radiometric datings suggest that the granites and rhyolites of the Grong-Olden Culmination were formed around 1650 Ma ago (Stuckless et al. 1982, Wilson 1982, Wilson et al. 1985). Reworking in the Grong-Olden Culmination is limited to the Caledonian deformation and metamorphism, in contrast to the Western Gneiss Region, which is a polymetamorphic region with events in Svecofennian, Sveconorwegian-Grenvillian and Caledonian time (Brueckner 1979, Corfu 1980, Gebauer 1983, Gorbatshev 1985).

Based on age relationships, geochemistry and lithological similarities, the Grong-Olden Culmination and the Tömmerrås Window are generally considered to belong to the Transscandinavian Granite Porphyry Belt of I-type granites and associated acidic volcanic rocks. This belt extends from southern Sweden to northern Norway. (Wilson et al. 1985, Gorbatshev 1985, Patchett et al. 1986). Its rocks were formed during a long period of time between c. 1800 Ma (southern Sweden: Åberg and Persson 1984, Patchett et al. 1986) and 1650 Ma (northern and central Sweden: Wilson et al. 1985, Patchett et al. 1986). The igneous belt is therefore not the result of a single distinct magmatic episode.

The Vestranden gneiss area is the northernmost part of the Western Gneiss Region. The crust of the latter region formed coevally with that of the southwestern Scandinavia (Gorbatshev 1985). This correlation is based on geochronological and lithological similarities between the southern and central parts of the Western Gneiss Region, southern Norway and south-western Sweden. With the exception for three Rb-Sr datings by Priem et al (1968) and one by Råheim et al. (1979) no datings of basement rocks from Vestranden have been published. However, recently a number of radiometric datings of different lithologies have been made in co-operation between the Department of Geology at Lund University and the Laboratory for Isotope Geology at the Swedish Museum of Natural History in Stockholm.

The purpose of the present paper is to discuss one of these datings concerning the age of the Geitfjellet granite and the age of migmatitization of this granite. Another aspect is the correlation of this granite the similar Revsund granite occurring in the Caledonian foreland.

One zircon U-Pb dating, ten whole-rock Rb-Sr isotope analyses and five chemical analyses form the basis of the discussion.

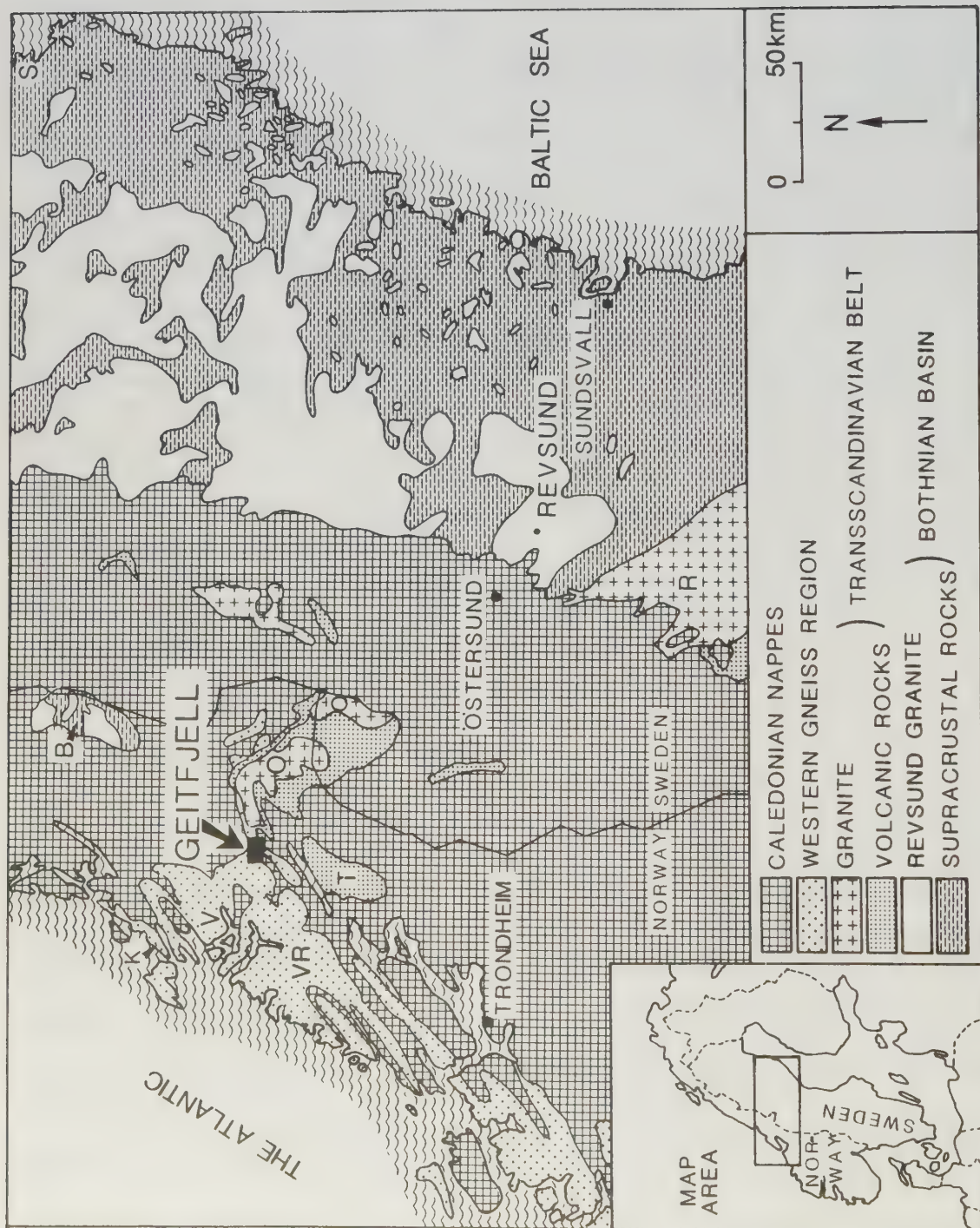


Fig. 1. Simplified geological map of northern central Sweden, compiled from Gavelin (1955), Greiling (1982), Troeng (1982), Lundegårdh et al. (1974), Sigmond et al. (1984) and Johansson (unpublished results). Abbreviations: B = Börgefjell Window, K = Kolvereid, O = Olden granite, R = Råtan granite, S = Skellefteå, T = Tömmerså Window, V = Vetrihusbotnet, VR = Vestranden.

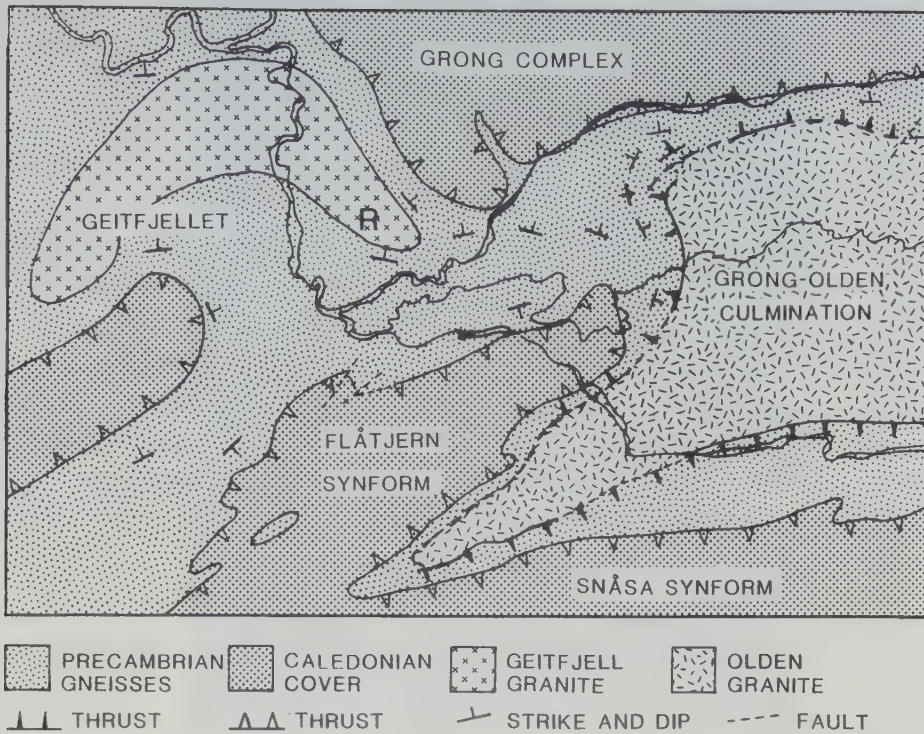


Fig. 2. Geological map of the Geitfjellet area. The outcrop pattern of the westernmost part of the Geitfjellet granite is based on the map by Sigmond et al. (1984).

Geological setting

The Geitfjellet granite occurs in the easternmost part of Vestranden (Fig. 1, 2). It forms a less than 500 m thick slice of coarsely porphyritic, very inhomogeneously deformed, grey rock consisting of microcline, quartz, oligoclase (An 20-25) and biotite. Accessory minerals are muscovite, hornblende, zircon, apatite, chlorite, garnet, fluorite, allanite, opaque minerals, and occasionally diopside. The muscovite was formed together with magnetite by the breakdown of biotite. Chlorite replaces biotite and at least some of the muscovite. Myrmekites are common and in some thin sections, the feldspar phases are string perthites. The feldspar megacrysts reach up to 6 cm in length. Brown biotite is the only major Fe-Mg phase in the granite. Diopside occasionally occurs in the coarse-grained granite at Rognsmoklumpen (R in Fig. 2).

Diopside and garnet are also found in tonalitic xenoliths at Geitfjellet. The diopside is always more or less replaced by hornblende which together with biotite and elongated quartz domains define the regional foliation.

For the very coarse-grained granite it is difficult to obtain a representative modal composition. In many places, the intense deformation transformed granite into augen gneiss. In some places, aplitic layers, thin metabasites and tonalitic

xenoliths are sheared and almost isoclinally folded together with the augen gneiss. In these cases only a very small angular discordance between the foliation and the xenolith contact can be seen. Elsewhere the Geitfjellet granite is well preserved (Fig. 3). While most geologists consider that the regional foliation is a result of Caledonian deformation, Råheim et al. (1979) suggested a Svecofennian age. This suggestion was discussed and rejected in by Johansson (1986). For details the reader is referred to that paper.

Stratigraphically above the granite slice there is a sequence of predominantly red and grey fine-grained gneisses interbanded by numerous amphibolite layers. Mica schists and quartzites are occasionally found. Some metres or some tens of metres thick units of coarse to medium grained augen gneisses occur in the upper part of the fine-grained rock series. Similar, but somewhat more reddish granitic gneisses occur beneath the Geitfjellet granite. No tectonic or metamorphic break is found between the Geitfjellet granite and the surrounding gneisses.

Close to the top of Geitfjellet, the granite is partly migmatitic (Fig. 4). The regional foliation postdates the migmatite formation.

Sampling

Samples for chemical analysis and for radiometric dating were collected from newly blasted road cuts along a road to the top of Geitfjellet. In order to satisfy representative sampling of the coarse grained Geitfjellet granite (Fig. 3), five specimens of 6-7 kilograms each were taken for chemical analysis. For U-Pb zircon dating approximately 70 kilograms of the coarse grained granite were sampled. The samples for the zircon dating and geochemical analysis were taken within the same area and are petrographically identical. The samples for Rb-Sr whole rock dating were collected further up along the same road. The maximum distance between individual Rb-Sr sample points is approximately 20 m. The coordinates of the sample sites are listed in the appendix together with short petrographic descriptions of the Rb-Sr whole rock samples.

Geochemistry

An extensive geochemical investigation of the Geitfjellet granite is beyond the scope of this paper. It must be emphasized that the geochemistry is representative only for the coarse-grained granite type (Fig. 3) at Geitfjellet.

SiO₂, TiO₂, Al₂O₃, total iron as Fe₂O₃, CaO and K₂O were determined by X-ray fluorescence employing glass discs. MgO, MnO, and Na₂O were analysed by atomic absorption while FeO was titrated potentiometric. The trace elements Rb, Sr, Zr and Nb were determined by X-ray fluorescence using powder pellets. Calibration of the instruments were performed with "home standard" which have been extensively analyzed against international reference samples. Some details of the employed procedures and the quality of the analytical work are described in Solyom et al. (1984).



Fig. 3. Typical coarse-grained grey Geitfjellet granite. The length of the hammer is 55 cm.



Fig. 4. Migmatite patches in deformed Geitfjellet granite near the top of the Geitfjellet mountain. The length of the scale is 10 cm.

IV- 7

Table 1. Chemical composition and CIPW norms of the Geitfjellet, Revsund and Olden granites. PERAL = The molar ratio of Al_2O_3 to $(\text{Na}_2\text{O}+\text{K}_2\text{O}+\text{CaO})$, D.I. = Sum of normative quartz, albite and orthoclase (differentiation index of Thornton & Tuttle (1960). x = average value ; s = standard deviation.

	GEITFJELLET		REVSUND I		REVSUND II		OLDEN	
	x	s	x	s	x	s	x	s
SiO_2	71.48	0.22	70.75	1.02	69.89	3.36	75.2	2.2
TiO_2	0.33	0.01	0.46	0.22	0.52	0.25	0.16	0.9
Al_2O_3	14.10	0.06	14.08	0.72	14.08	0.88	13.0	0.09
Fe_2O_3	0.31	0.03	0.41	0.26	0.43	0.31	0.4	0.3
FeO	2.27	0.08	2.80	0.68	3.24	1.26	1.1	0.4
MnO	0.03	----	0.07	0.11	0.06	0.05	0.04	0.02
MgO	0.44	0.02	0.59	0.23	0.73	0.45	0.18	0.18
CaO	1.45	0.03	1.64	0.46	1.82	0.69	0.6	0.4
Na_2O	2.77	0.02	2.76	0.42	2.78	0.54	3.7	0.4
K_2O	5.72	0.10	4.88	0.45	4.61	0.67	5.1	0.4
Nb	15	0.5	----	----	----	----	----	----
Rb	248	5	----	----	----	----	----	----
Sr	133	2	----	----	----	----	----	----
Zr	194	6	----	----	----	----	----	----
n	5		26		99		35	

CIPW NORM:

Quartz	28.2	29.7	28.8	31.9
Orthoclase	33.7	28.8	27.2	30.1
Albite	23.5	23.4	23.5	31.3
Anorthite	7.2	8.1	9.0	3.0
Corundum	0.7	1.3	1.2	0.3
Hypersthene	3.4	4.2	4.9	1.5
Enstatite	1.1	1.5	1.8	0.5
Ilmenite	0.6	0.9	1.0	0.3
Magnetite	0.5	0.6	0.6	0.6
PERAL:	1.05	1.10	1.09	1.02
D.I.	85.4	81.9	79.5	93.3

The small standard deviations seen in major and trace elements (Table 1) show that the samples were large enough to be representative of the coarse-grained granite.

For comparison, analyses of the nearby Olden granite and the Revsund granite are shown in Table 1. The Olden granite occupies the major part of the Grong-Olden Culmination (Fig. 1). The geochemistry and isotope geology of the Olden granite were discussed by Troeng (1982) and Stuckless et al. (1982) respectively. The Revsund granite occurs as large massifs east of the Caledonian Front and will be considered below. The molar oxide ratio of Al_2O_3 to $\text{Na}_2\text{O} + \text{K}_2\text{O} + \text{CaO}$ (PERAL in Table 1) is slightly larger than 1.0, which indicates a weak peraluminous character. This is also reflected by the presence of normative corundum (Table 1).

Analytical procedures for radiometric dating.

From the granite sample, zircons in ample quantities were separated using standard techniques. The most non magnetic fraction was further split into size fractions from which well defined zircon crystals were chosen after ocular inspection. U and Pb were extracted from the zircons and isolated for mass spectrometry following the method of Krogh (1973), with some modifications described by Christiansson (1982) including electrolytical collection of Pb. U content was determined on an AVCO 901-A and the isotopic ratios of Pb were measured using a MAT 261 mass spectrometer.

Calculations of isotopic compositions and ages were made according to Ludwig (1980) using the decay constant recommended in Steiger and Jäger (1977). Mass fractionation corrections of 0.10 % / AMU for U and 0.12 % / AMU for Pb were made. The total Pb contamination was on average 2.4 ng and to compensate for common Pb the following values were used: $206/204 = 15.8$, $207/204 = 15.3$, and $208/204 = 35.4$.

In order to study the homogeneity of the zircons and the possible presence of older inherited cores, all size fractions except $< 45 \mu\text{m}$ were abraded until on average 58 % of the initial mass remained, after which a new analysis was performed. The abrasion was achieved by long and gentle polish in an air abrasion device, constructed and operated according to Krogh (1982), with the exception that no pyrite was used.

The Rb-Sr samples were milled to powder. The Rb/Sr ratios and approximate contents of these elements were determined by XRF spectrometry using a Philips PW 1140 generator. After HF-HClO_4 dissolution followed by cation exchange purification of Sr, performed as described by Christiansson (1982), the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios were measured on a MAT 261 mass spectrometer. Normalisation to $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$ was made. The accuracy is better than 0.0001 (1 sigma). From these measurements $^{87}\text{Rb}/^{86}\text{Sr}$ ratios were calculated and are here given in Table 3 with an accuracy of 0.6 %. The Rb-Sr whole rock ages and initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios were estimated with the method of Williamson (1968) and the decay constant $1.42 \times 10^{-11} \text{ a}^{-1}$ for ^{87}Rb (Steiger and Jäger 1977). Errors are given as 1 sigma.

Results of the radiometric datings.

U-Pb dating.

Most zircons have subhedral outlines with well developed prismatic shapes and less well developed pyramidal terminations (Fig. 5a). The length/width ratio is approximately 2.5. The colour is light brown to light grey. Backscatter electron images reveal the compositional zoning of the zircons as dark and light areas in Fig. 5b. The intensity is proportional to the average atomic weight of the present elements (light areas = heavy elements and vice versa). A majority of the zircons are compositionally zoned (Fig. 5c). Most zircons have a zoning which is concordant to crystal growth planes and therefore do not represent older inherited zircons. In other zircons there is a thin outer zone of zircon which is discordant to the crystallographic planes of the internal part of the zircon (Fig. 5c). The outer shell has an idiomorphic outline and consists of pure zircon, while the inner part consists of impure zircon. This compositional difference is too small to be analyzed with an energy-dispersive micro probe but it can be detected by the very sensitive backscatter technique. The outer shell most likely represents a recrystallized part of the zircon. This suggestion is supported by the discordant behaviour, the pure zircon (refined ?) of the shell and that fractures in the inner part often stop at the outer shell.

The analytical data are shown in Table 2. When all the zircon fractions are regressed, the obtained discordia has an upper intercept age of 1808 ± 18 Ma and a lower intercept age of 449 ± 42 Ma. The MSWD value for this line is 3.9. This comparatively high MSWD is largely caused by the misfit of the non-abraded 74-106 μm fraction. When the zircons of this fraction were abraded and analysed, the obtained data fitted very well with the discordia. If the non-abraded 74-106 μm fraction is excluded from the age calculation the resulting upper intercept age is 1823 ± 21 Ma, the lower intercept age is 487 ± 45 Ma and the MSWD value is 1.1. Since most published age datings made on zircons only consider non abraded fractions it is of interest to do the same for the Geitfjellet zircon fractions. When all the non abraded zircon fractions are regressed together the resulting upper intercept age is 1740 ± 62 Ma, and if the fraction 74 - 106 μm is excluded, the obtained age is 1775 ± 70 Ma with the lower intercept age 373 ± 184 Ma. The MSWD value can be reduced from 4.0 to 0.0 by excluding the 74 -106 μm fraction.

The U and Pb content in the different zircon fractions are quite uniform except for the abraded > 150 μm fraction which has a considerably higher U and Pb content. All data from abraded zircons, except the > 150 μm fraction are less discordant than the data for the non abraded zircons of the same size fraction.

There are small differences in the U and Pb contents of the non abraded zircons and the internal parts of the zircons (Table 2). The abrasion of the zircons results in a higher upper intercept age suggesting that there is an age difference between internal and outer parts of the zircons. The results from regression of different size fraction combinations are summarized in Table 3.

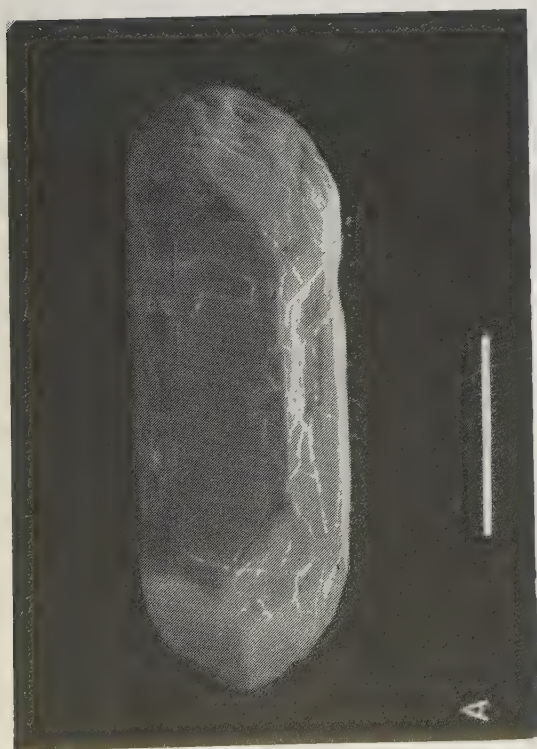
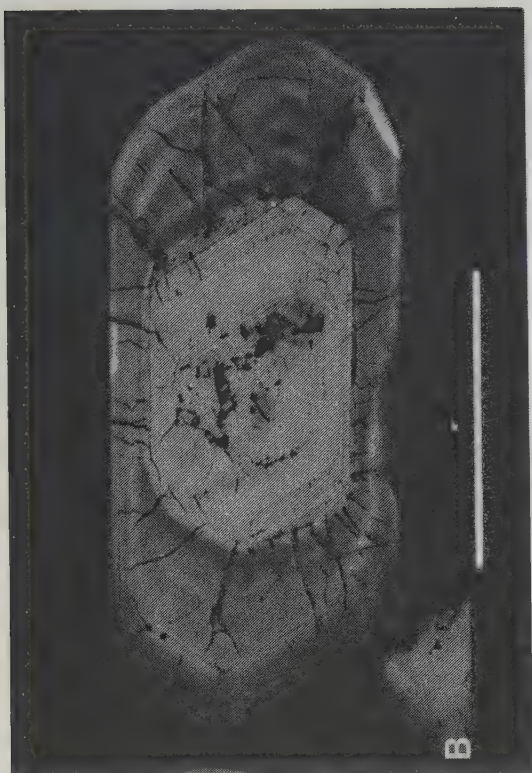


Fig. 5 A: Zircons from the Geitfjellet granite.

B: Backscatter electron image of a sectioned zircon. Note the concordance between crystal growth planes and the compositional zoning.

C: Backscatter electron image of a zircon with a thin discordant shell. Note that some of the fractures stop at the outer shell. The length of the scale bars are 100 μm .

Table 2. U-Pb analytical data from the Geitfjellet granite.

No.	Fraction μm	Concentration in ppm		Isotopic ratios			Age in Ma		
		U	Pb _{rad}	a $\frac{^{206}\text{Pb}}{^{204}\text{Pb}}$	b $\frac{^{207}\text{Pb}}{^{206}\text{Pb}}$	b $\frac{^{208}\text{Pb}}{^{206}\text{Pb}}$	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$	$\frac{^{207}\text{Pb}}{^{206}\text{Pb}}$
1.	< 45	1181	247	41800	0.1025	0.0342	1251	1414	1670
2.	45-74	1163	247	62200	0.1028	0.0347	1268	1427	1675
2.	Abraded	1134	242	32400	0.1029	0.0347	1271	1431	1677
3.	74-106	1102	233	7675	0.1030	0.0364	1261	1425	1679
3.	Abraded	1178	259	33300	0.1035	0.0364	1305	1458	1688
4.	106-150	1133	247	> 100000	0.1033	0.0346	1299	1452	1684
4.	Abraded	1115	245	64100	0.1036	0.0359	1303	1457	1690
5.	> 150	1164	251	39000	0.1029	0.0352	1283	1439	1678
5.	Abraded	1369	288	37200	0.1025	0.0313	1260	1420	1670

a) Corrected for blank and mass discrimination

b) Corrected for mass discrimination, blank and common lead

Table 3. Summary of different regression alternatives.

	n	Upper intercept- age (Ma).	Lower intercept- age (Ma).	MSWD- value.
All abraded zircon fractions	4	1830 ± 26	501 ± 56	2.1
All zircon fractions except 74-106 μm	8	1823 ± 23	487 ± 45	1.1
All zircon fractions	9	1808 ± 18	449 ± 42	3.9
All non abraded zircon fractions except 74-106 μm	4	1775 ± 70	373 ± 184	0.0
All non abraded zircon fractions	5	1740 ± 62	259 ± 200	4.0

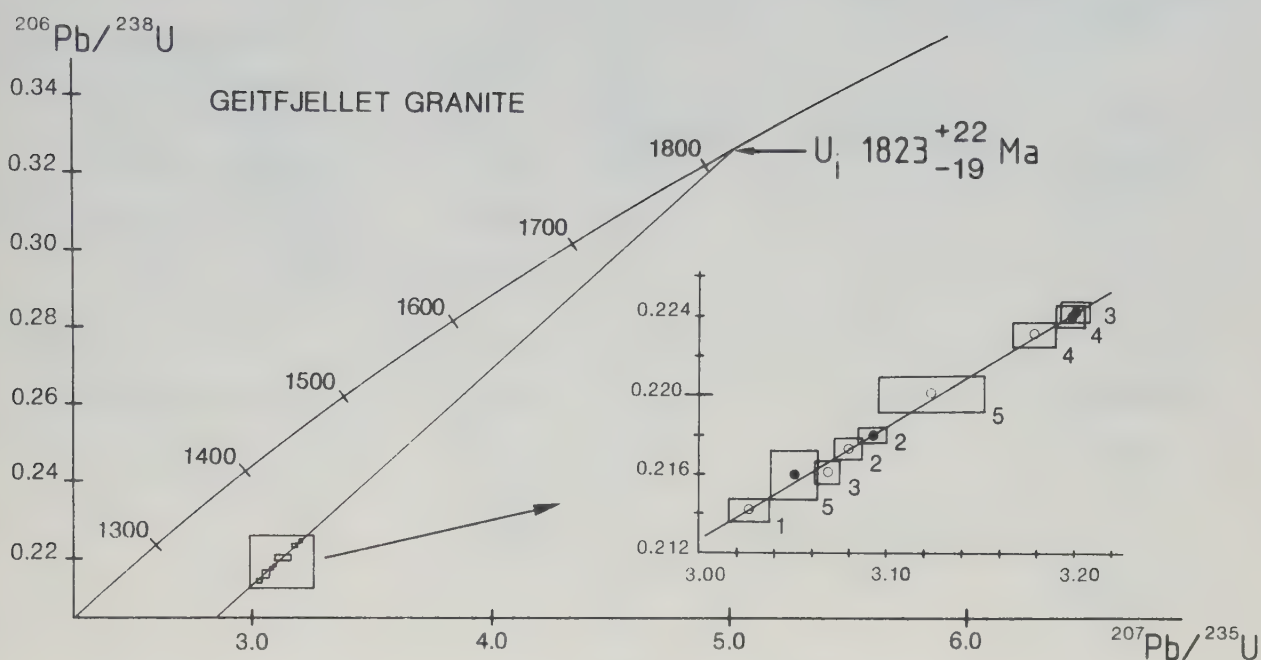


Fig. 6. U-Pb concordia plot of zircons from the Geitfjellet granite. Open circles = non abraded zircon fractions; filled circles = abraded fractions. The zircon fractions are numbered in accordance with Table 2. The lower intercept age is 487 ± 45 Ma. MSWD value is 1.1.

Rb-Sr dating.

Amongst the ten analysed whole-rock samples, three derive from migmatite neosomes, the other samples represent different types of granite or rocks clearly related to the formation of the Geitfjellet granite (Appendix).

The Rb-Sr data are listed in Table 4 and plotted in the isochron diagram (Fig. 7) where a clear difference between the migmatitic samples and the non migmatitic samples is seen. The seven non-migmatitic rocks yield an age of 1784 ± 11 Ma with an initial $^{87}\text{Sr}/^{86}\text{Sr}$ -ratio of 0.7086 ± 0.0008 , MSWD = 11.8. The data from the three migmatitic samples fail to yield a well-defined regression line. A combination of all three points indicates an age of 1649 ± 20 Ma with a very large MSWD (81).

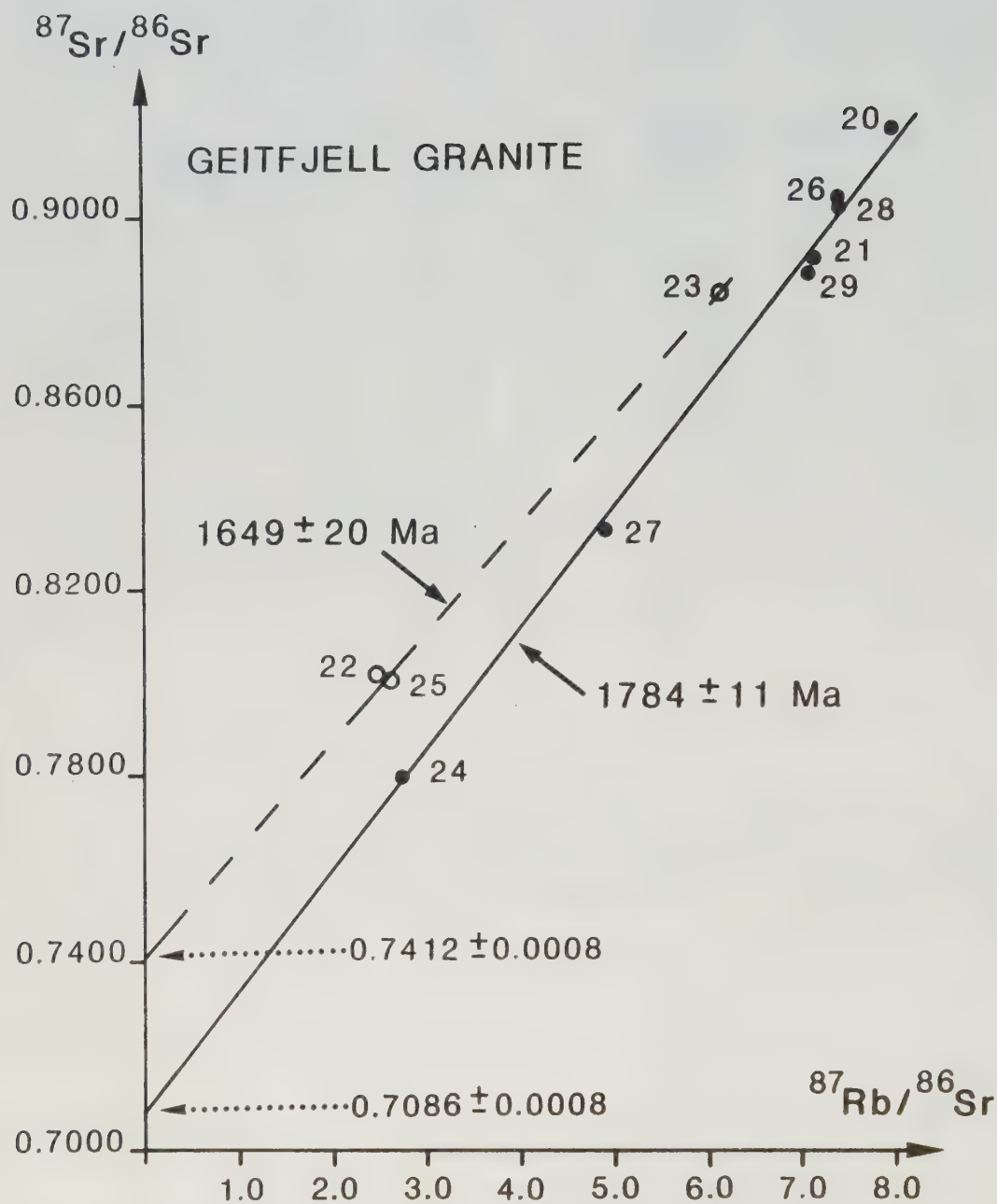


Fig. 7. Rb-Sr diagram for the Geitfjellet whole rock samples. Neosome samples are shown with open circles.

Table 4. Rb-Sr analytical data for the Geitfjellet rocks.

No:	Rock type	Rb (1) (ppm)	Sr (1) (ppm)	$^{87}\text{Rb} / ^{86}\text{Sr}^{(2)}$	$^{87}\text{Sr} / ^{86}\text{Sr}^{(3)}$
20	Pegmatite	333	122	8.04	0.9183
21	Augen gneiss	258	106	7.17	0.8994
22	Granite (<i>neosome</i>)	153	178	2.50	0.8015
23	Granite (<i>neosome</i>)	227	111	6.03	0.8838
24	Hybride rock	210	223	2.74	0.7799
25	Granite (<i>neosome</i>)	159	175	2.65	0.8002
26	Coarse augen gneiss	263	104	7.45	0.9032
27	"- "- "-	245	146	4.94	0.8324
28	"- "- "-	261	103	7.46	0.9018
29	"- "- "-	263	109	7.13	0.8876

(1) XRF, approximate content

(2) XRF and MS, estimated precision $\pm 0.6 \%$ (3) MS, typical precision $\pm 6 \cdot 10^{-5}$

	GEITFJELLET	REVSUND	OLDEN
$^{87}\text{Sr}/^{86}\text{Sr} =$	0.7078 - 0.7094	0.7067 - 0.7082 ^a	0.7092 - 0.7104 ^b
			0.7122 - 0.7146 ^c

^a Welin 1970^b Klingspor & Troeng 1980^c Stuckless & Troeng 1984

Discussion.

The 1823 Ma age of the Geitfjellet granite shows that this granite is not related to the granites of the Transscandinavian Granite Porphyry Belt in the Grong-Olden Culmination or in the Tömmerrås Window. The Olden granite is chemically different from the Geitfjellet granite and shows more marked I-type granite characteristics (Chappel & White 1974), (Table 1).

In contrast the Geitfjellet granite is closely similar to coeval granites of the Revsund massifs. The geochemistry, and the O, Sr, Sm-Nd isotope data of the Revsund granite suggest that the granite has been formed by large scale anatexis of metasediments, mostly greywackes (Gavelin & Grip 1946, Gavelin 1955, Svensson 1970, 1979, Wilson 1982, Wilson et al. 1985, Patchett et al. 1986). It was intruded into metasediments and volcanic rocks of the Bothnian basin in Jämtland and Västerbotten (Fig. 1).

According to Patchett et al. (1986) the source material for the Revsund granite contained about 20 % of an Archean component. The Revsund granite massifs are very large and consist of many smaller plutons. The Revsund granite is petrographically and geochemically surprisingly homogeneous over large areas from northern Västerbotten to the type area in central Jämtland, 200 km farther south. The geochemistry of different Revsund plutons have been studied by Svensson (1970, 1979), Einarsson (1978) and Person (1978). The typical Revsund granite is a grey, coarse-grained porphyritic rock with K-feldspar megacryst up to 6-7 cm in size. Even-grained and reddish varieties occur locally. The granite is enriched in U, W, Sn and Mo (Gavelin 1955, Wilson & Åkerblom 1982, Wilson et al. 1985, J. Trägård pers. comm. 1985).

The Geitfjellet granite is petrographically and chemically very similar to the Revsund granite (Table 1). The Revsund I group consists of 26 selected analyses of grey coarse grained porphyritic granite from Västerbotten (Svensson 1970) with an average SiO_2 content close to the average SiO_2 content of the Geitfjellet granite. The Revsund II group comprises 99 analyses of coarse grained grey porphyritic granite. The samples of the Revsund II group were collected in an area larger than 22000 km^2 in Västerbotten (Svensson 1970). There are only small differences between the chemistries of the two granites. The average composition of the Geitfjellet granite is within the range of the Revsund average $\pm$ the standard deviation. The only exception is K_2O which is somewhat higher in the Geitfjellet samples. The age of some Revsund granite massifs have been determined by the U-Pb zircon method. The results show that the granites formed in the interval 1770 to 1790 Ma ago (Wilson et al. 1985, Patchett et al. 1986). These datings are based on non abraded zircons and are in very good agreement with the 1775 ± 70 Ma age for the non abraded Geitfjellet zircons excluding the 74-106 μm fraction.

Also the $^{87}\text{Sr}/^{86}\text{Sr}$ initial ratios of the Revsund granite (0.7067 - 0.7082) (Welin et al. 1971) compare closely to those of the Geitfjellet granite (0.7078 - 0.7094).

Coarse-grained grey granite of the Geitfjellet type also occurs farther west in the Vestränden area. At Vetrhusbotnet northwest of Geitfjellet, (Fig. 1)

coarse-grained grey granite occurs in roadcuts in an otherwise unmapped area. This granite is probably much larger than the Geitfjellet granite (R. Boyd pers. comm. 1985, aerial photographs).

Farther north, in the Kolvereid area (Fig. 1), zircons from tonalitic rocks have yielded an age of 1820 ± 42 Ma (Schouenborg et al. in prep.) while three Rb-Sr datings of basement gneisses (Priem et al. 1968) gave ages in the interval 1763 - 1864 Ma (recalculated for a decay constant of $1.42 \cdot 10^{-11} \text{a}^{-1}$). Preliminary results (Schouenborg et al. in prep.) also show that Precambrian calc-silicate gneisses and other rocks of supracrustal origin in the northern part of Vestranden exists. These results all together suggest that the northern part of the Western Gneiss Region i.e. Vestranden is probably a western continuation of the Svecokarelian province of Västerbotten (Bothnian basin) and Jämtland.

This inference is also supported by the similarity between the granites in the Börgefjäll Window and the Revsund granites (Kautsky 1948, Zachrisson 1969, Gustavson 1973, Greiling 1974, 1982). The Börgefjäll Window (Fig.1) is situated approximately halfway between the Revsund provinces in Västerbotten and Vestranden. The window is dominated by coarse porphyritic granite of the Revsund type (Greiling 1982). There are also Precambrian rocks of supracrustal origin which may correspond to the metasediments and metavolcanites of the Bothnian basin farther east. Granodiorites and syenites occur in subordinate amounts. The latter rocks may possibly be correlated with intrusions belonging to the Trans-Scandinavian Granite Porphyry Belt.

An important aspect of the correlation between Revsund granite and the Geitfjellet-Vettrhusbotnet granite is that since the Revsund granite type is enriched in Mo, W, Sn and U, large areas in Vestranden may be promising areas for prospecting for these metals.

Another important result of this study is that if the Vestranden area represents the westward continuation of the Bothnian basin region, there is a possibility that not only the granites of that region, but also greywackes, pelites, pillow-lavas, metavolcanites and other supracrustals may occur in Vestranden. These rocks could very well be masked by Caledonian metamorphism and deformation and "hidden" in the numerous "cover"-sequences that occur in many places in the Vestranden area. The rocks of the Bothnian basin are petrogenetically unrelated to the Caledonian orogenic evolution, but since the Bothnian basin may represent an outer arc accretionary prism environment (Wilson et al. 1985) they may have many petrological and metamorphic features in common with the rocks of the corresponding Caledonian geotectonic environments. The Bothnian rocks may also well have been tectonically incorporated in the Caledonian nappes that were derived from the outer parts of the Baltoscandian margin. Therefore, the importance of radiometric and isotope geological studies must be emphasized whenever there is reason to suspect a mixed origin.

In conclusion, there are striking petrographical, geochemical, isotope geological and age similarities between the Geitfjellet and Revsund granites. Based on this fact and on the occurrence of other Svecokarelian granitoids in Vestranden, it can be concluded that the northernmost part of the Western Gneiss region

(Vestranden) most likely is a western continuation of the Svecokarelian province of central Sweden.

Appendix

Description of Rb-Sr whole-rock samples.

All Rb-Sr samples consist of quartz, K-feldspar, plagioclase, and biotite. Accessory minerals are muscovite, apatite, zircon, $\pm$ allanite, $\pm$ garnet, $\pm$ chlorite. The samples for U-Pb dating and geochemical analysis were taken at UTM coordinate : UM 685 478 and for Rb-Sr dating at: UM 662 460. These coordinates refer to map sheet Grong 1:50 000.

Sample no. : 20. Pegmatite, forming pods and patches in the granite. The pegmatite pod is not intruding the granite but represents a late magmatic phase in the crystallisation of the granite. It is slightly foliated.

21. Reddish well foliated augen gneiss. The augens consist of numerous small microcline crystals. Many augens are strongly elongated and flattened. The average diameter of the least deformed augens are approximately 20 mm. Plagioclase, quartz and biotite occur as inclusions in the augens. The matrix is dominated by quartz, K-feldspar, plagioclase and biotite.

22. (Neosome). White medium grained and even-grained granite from the migmatite-neosome. The granite is only slightly foliated. Biotite is very subordinate. Small garnets (< 0.5 mm) are common.

23. (Neosome). Reddish medium-grained granite with well developed granitic texture and almost no foliation visible. The sample comes from a migmatite neosome.

24. Hybrid rock occurring along the margin of a xenolith, partly assimilated in the granite. The contact zone is 10 -15 cm wide. The rock is light grey, fine-grained and rich in biotite and plagioclase.

25. (Neosome). White to light grey granite from a migmatite neosome. The rock has a diffuse banding with cm wide bands somewhat richer in biotite. Small garnets (< 0.5 mm) are common.

26 - 29. Coarse augen gneiss with K-feldspar megacrysts up to 6 cm across. These four samples are almost identical to the rock sampled for the zircon dating.

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PAPER V

AN OCCURRENCE OF THE GULA NAPPE IN WESTERN GNEISS REGION,
CENTRAL NORWEGIAN CALEDONIDES.

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AN OCCURRENCE OF THE GULA NAPPE IN THE WESTERN GNEISS REGION, CENTRAL NORWEGIAN CALEDONIDES.

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Abstract

At Fosslia (100 km NNE Trondheim, Western Gneiss Region), a cover sequence of metasedimentary and metavolcanic rocks overlies migmatitic gneisses and subordinate mafic rocks of the Precambrian crystalline basement. While structural parallelism characterizes the basement-cover contact, a marked structural contrast exists between internal parts of the cover and the basement.

The cover comprises micaceous gneisses, quartz veined gneisses, quartz-feldspar gneisses, quartzites, felsites, amphibolites, graphitic schists, and mica schists. A rusty weathering mica schist contains a sulphide mineralization. These lithologies compare well with those of the Gula Nappe in the Trondheim Nappe complex. This correlation is strengthened by radiometric dating of zircons from a granodioritic dyke intruding the cover. The dyke is restricted to the cover sequence. The U-Pb zircon age is 430 ± 12 Ma. This age is close to those obtained on trondhjemitic dykes in the Gula Nappe in the Trondheim Complex. The Fosslia occurrence provides additional evidence of the existence of isolated Caledonian cover units in the northern part of the Western Gneiss Region and that such units can be identified despite intense deformation and amphibolite facies metamorphic conditions. It also supports the interpretation that the cover succession is allochthonous in relation to the underlying basement.

Introduction.

Vestranden is the northernmost part of the Western Gneiss Region (WGR) in Norway. This Precambrian realm has a critical implication in the interpretation of the Caledonide Orogen. In this area, the behaviour of the basement during the Caledonian event can be studied. Cratonic and miogeoclinal elements of the Baltoscandian margin occur in several nappes of the Lower-Upper Allochthons. The source area of these elements could have been a westerly continuation of the WGR. The pressure-temperature-time (PTt) evolution of the WGR and the relationship between metamorphism in the WGR and in the overlying Caledonian nappes are critical factors in reconstruction of the tectonothermal evolution of the Caledonides. However, the Vestranden region is not only crucial in the interpretation of the Caledonian accretional growth. Paradoxically, however, the geology of the Vestranden area has been little explored. This concerns in particular the numerous occurrences of supracrustal rocks of which some are westerly extensions of the Trondheim Nappe Complex (TNC). The TNC comprises the Gula and Stören Nappes. Both these nappes represent outboard terranes which prior to the Caledonian thrusting were situated to the west of the Baltoscandian margin. Identification of westerly situated, solitary cover units in the WGR and their

correlation with the well known Caledonian allochthon is important since it constrains the timing of deformation and metamorphism in the basement. Occurrences of Caledonian allochthonous units in WGR would also confirm that the nappes were thrust across this region. Attempts to trace the allochthon from the Trondheim region into the WGR are few but promising (Krill 1980, Kollung 1984, Schouenborg in press, Tucker in prep.). In the WGR, the cover is generally tightly and often recumbently folded together with the Precambrian gneisses. Basement-cover contacts are concordant and commonly recrystallized. The westwards gradually increasing "Caledonization" of the basement-cover contacts has been described by a.o. Bryhni & Brastad (1980) and Koestler (1984).

The present paper considers an isolated occurrence of Caledonian allochthonous cover located in Precambrian gneisses at Fosslia, only 40 km from the Atlantic coast (Fig. 1). The new geological map of Norway (Sigmond et al. 1984) describes the Fosslia cover unit as a mica schists and mica gneisses of Precambrian and/or Cambro-Silurian age. Identification of the Fosslia cover as an unit of the TNC is based on lithological correlation between the Fosslia occurrence and parts of the Caledonian allochthon in the Snåsa region, previously studied by two of us (Andreasson & Johansson 1982). In addition, a radiometric dating has been undertaken.

Geology

The Fosslia cover succession comprises about 800 metres of essentially supracrustal rocks (Fig. 2). An almost complete section is exposed immediately to the west of the farm Fosslia along road 724 between Namdalseid and Osen. The UTM koordinate for the Fosslia locality is 32W PS 4 70 2 7 0 on map sheet 1623 I Jössund (1:50 000). Other exposures are found in the Öyungåa river canyon and south of the canyon.

Migmatitic gneisses of mainly granitic composition and subordinate mafic bodies form the Precambrian *basement* surrounding the Fosslia cover unit. Farther west in Osen, a preliminary U-Pb zircon age of 1630 ± 80 Ma has been obtained for similar migmatitic gneisses (Johansson et al. unpublished results).

The Fosslia *cover* comprises micaceous gneisses, quartz-veined gneisses, quartz-feldspar gneisses, quartzites, amphibolites, a characteristically mineralized metavolcanic/metasedimentary rock association and granodioritic dykes. Due to the intense folding it is not possible to establish any lithostratigraphic order. The continuation and geometry of the infolded cover was not investigated. The mineralized metavolcanites/metasediments and the dykes are of particular interest for the correlation with the TNC east of Vestranden area. The former include fine-grained, garnetiferous and sulphide-bearing amphibolite; sulphide-rich garnet-staurolite mica schist, and thin lenses of sulphide ore and garnetiferous ore. Sulphide phases are pyrite (predominating) and pyrrhotite. The garnets of the sulphide ore and sulphide-rich mica schist are almandines with high contents (c. 20 wt-%) of spessartine. This lithological association is newer found in the Vestranden basement. In the micaceous gneisses, fibrolitic sillimanite is the stable alumina-

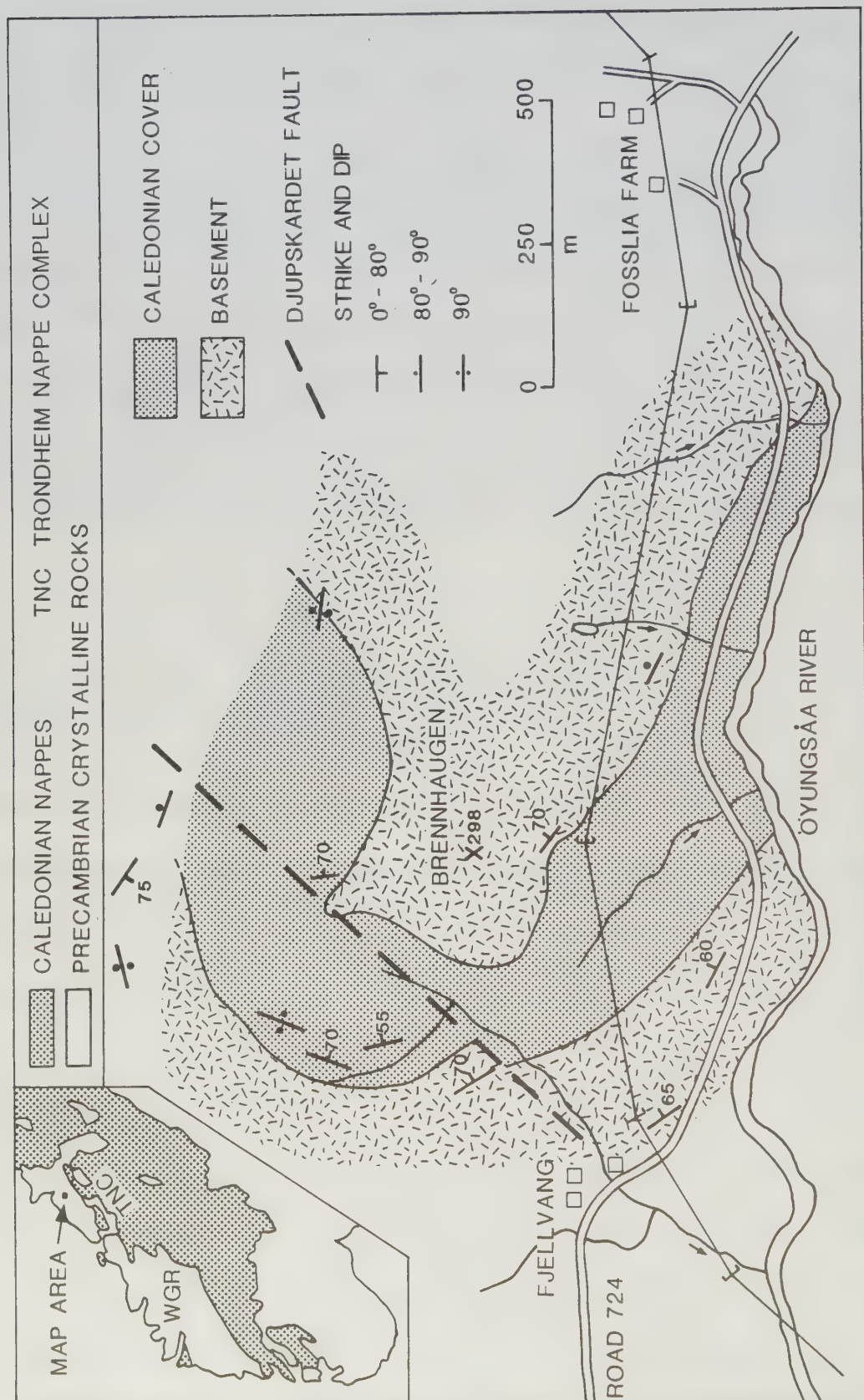


Fig. 1. Basement-cover map of the Fossilia area.

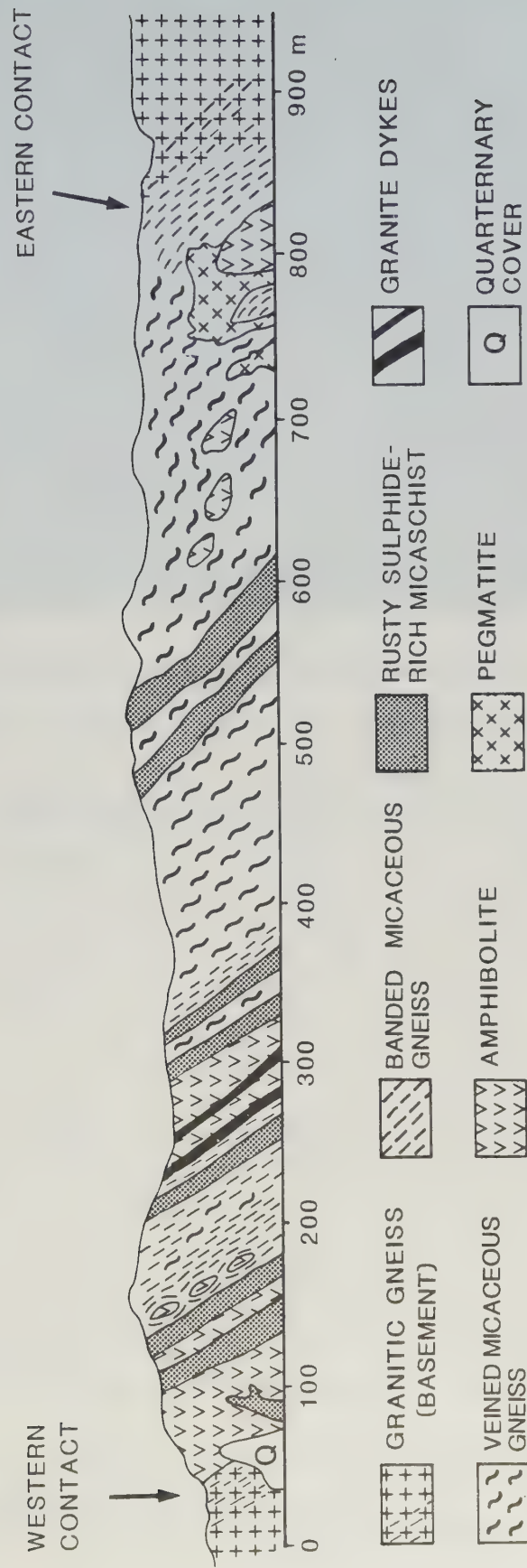


Fig. 2. Cross-section of the Fossilia cover sequence. The height of the road section is less than 10 meter.



Fig.3. Granite dyke (light grey) in the Fossilia road-cut. Length of hammer is 55 cm.

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silicate. Kyanite predating the sillimanite is occasionally found.

Two granodioritic dykes, 50 and 30 centimetres across, occur in the road section (Fig. 3). Due to deformation the dykes are concordant with the compositional banding of the host rock, at least on the scale of an outcrop. The Fossilia dykes are cut out at the basement-cover contact. The dykes consist of plagioclase, quartz, K-feldspar ($< 17\%$) and minor amounts of garnet, zircon and chlorite. The dykes have suffered amphibolite facies metamorphism. Northwest trending and northeast dipping compositional banding of the cover was multiply folded. The marked *structural contrast* between basement and cover is noteworthy and is not only the result of deviating deformational properties of the basement and the supracrustal rocks. The basement is characterized, essentially, by a single mature, foliation i.e. a thoroughly recrystallized or migmatitic gneissic banding. In contrast, the mesostructures of the cover include several generations of folds and foliations. Among structures easily observed in the road section, are east-west trending folds refolded along west-northwest trending axes. In the hinges of the latter folds, small quartz-feldspar veins define an axial-plane foliation. A late, northeast trending dextral fault (Djupskardet fault) displaced the cover rocks along their western contact.

The contacts between basement and cover are partly disturbed by pegmatites. However, a marked zone of secondary, tectonic conformity between basement and cover can be observed especially along the western contact of the road exposure

(Fig. 2). Here, the structures of both basement and cover have been transposed into a conspicuously straight and tight foliation. However, unlike the basement-cover contacts east of Vestranden. (e.g. in the Tömmerås Window and the Grong-Olden Culmination; Andreasson 1978, Johansson, paper II, this volume), the Fosslia contact is recrystallized and lacks phyllonites and mylonites.

Radiometric dating

Zircons from the two granitic dykes, in the Fosslia cover unit, were dated by the U-Pb method in an attempt to determine their age of intrusion and thereby estimate the maximum age of nappe displacement.

The size of the sample was approximately 60 kg of rock. The zircons were separated and divided into three nonmagnetic size fractions from which zircons were chosen by hand (Table 1). The chemical preparation procedure followed Krogh (1973) with a further purifying of the Pb fractions by electrodeposition on a Pt-electrode. The isotopic ratios of lead were determined on a MAT 261 and the uranium was analyzed on an AVCO 901-A mass spectrometer. The common lead correction was made assuming the following composition: $^{206}\text{Pb}/^{204}\text{Pb} = 18.0$, $^{207}\text{Pb} / ^{204}\text{Pb} = 15.6$, $^{208}\text{Pb} / ^{204}\text{Pb} = 37.8$. The total Pb blank contamination is 2.5 ng.

Table 1. U-Pb isotopic analyses of zircons from the Fosslia granitic dyke.

Fraction:	45 - 74 μm	74 - 106 μm	106 - 150 μm
U (ppm)	5540	10630	3630
Pb _{rad}	339	352	399
$^{206}\text{Pb} / ^{204}\text{Pb}$ a	8980	5130	3250
$^{207}\text{Pb} / ^{206}\text{Pb}$ b	0.05564	0.05547	0.05533
$^{208}\text{Pb} / ^{206}\text{Pb}$	0.00158	0.00147	0.00162
Age in Ma:			
$^{206}\text{Pb} / ^{238}\text{U}$	420	231	737
$^{207}\text{Pb} / ^{235}\text{U}$	423	250	664
$^{207}\text{Pb} / ^{206}\text{Pb}$	438	431	426

a = Corrected for blank lead and discrimination.

b = Corrected for blank lead, common lead and discrimination.

The age calculations followed Ludwig (1980) using the decay constants recommended in Steiger & Jäger (1977). The errors of the concordia ages are given as ± 2 sigma. The zircon morphology, degree of alteration and fracture frequency vary considerably between the different size fractions. All fractions are very rich in uranium (Table 1). The large zircons are often irregularly shaped and commonly consist of aggregates of smaller grains. Inclusions of plagioclase and K-feldspar occur. Fractures are present in all zircons, but are more frequent in the large grains (Fig. 4). Sometimes they are seen as networks on the grain surface. The medium- and small-size zircons have fewer fractures and often better developed crystal forms with pyramidal terminations. A thin, clear and inclusion free rim is often found. The very high uranium contents are partly explained by inclusions of uraninite (UO_2 Fig. 5). Energy-dispersive microprobe analyses also indicate the presence of ThO_2 in the inclusions. The inner parts of many zircons are severely altered. This alteration often follows fractures and certain crystal growth surfaces (Fig. 5). Analyses of the dark grey areas in Fig. 5 indicate increased contents of calcium and iron and indirectly also a fluid phase, most likely water. The altered areas protrude into fresh zircon where they form lobate contacts between fresh and altered zircon. It is worth noting that the degree of alteration is not related to the presence of uraninite inclusions. Entirely unaltered zircon without any sign of metamictization is commonly found around the uraninite inclusions.

When plotted in the concordia diagram, the Fossilia zircons yield an age of 430 ± 12 Ma (Fig. 6). This age is interpreted as a minimum estimate for the intrusion age of the dykes. One size fraction (106 - 150 μm) plots above the concordia and has probably lost uranium, while the two remaining fractions plot below the concordia suggesting lead loss. This seemingly disparate behaviour can be explained by differences of degree of alteration, fracture frequency and numbers of inclusions. The loss of uranium is in accordance with the observed severe alteration of many large-size zircons.

Thin, clear, rims on many zircons either represent a late-stage magmatic growth of younger zircon or crystal enlargement during later metamorphism. The only phase of metamorphism that can have caused the growth of the rims is the mid Silurian - early Devonian Scandian metamorphism. This fact and the very small volume of the rims exclude a significant Scandian influence on the obtained age. However, it is reasonable to interpret the age as a minimum estimate; the true age of intrusion may be somewhat older.

Discussion

The recognition of structural breaks and contrasts between the supracrustal succession and the migmatitic basement gneisses at Fossilia, and the occurrence of rootless Palaeozoic dykes in the supracrustals clearly indicate the presence of an isolated Caledonian allochthonous cover sequence. The allochthonous cover can be identified by comparison with well preserved lithologies in the eastern nappe terrains. Lithologies identical with those at Fossilia occur in the Gula Nappe of the

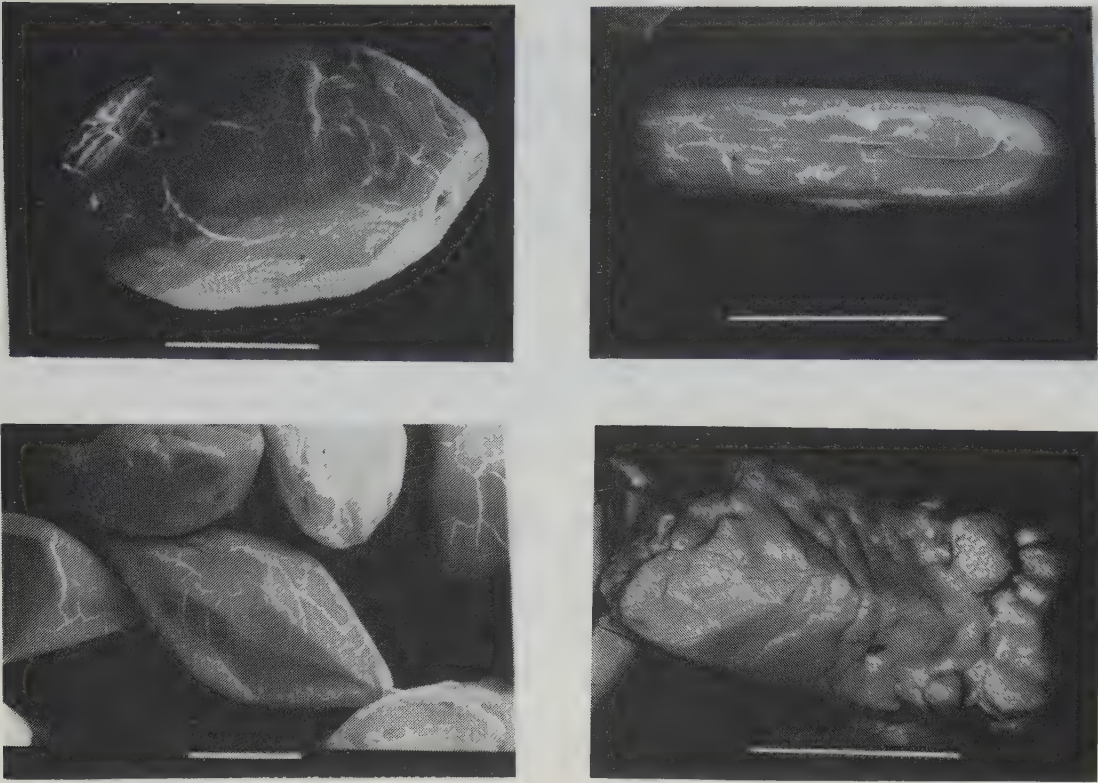


Fig. 4. Zircons from the Fossilia granitic dyke. The length of the scale bars are 100 μm .

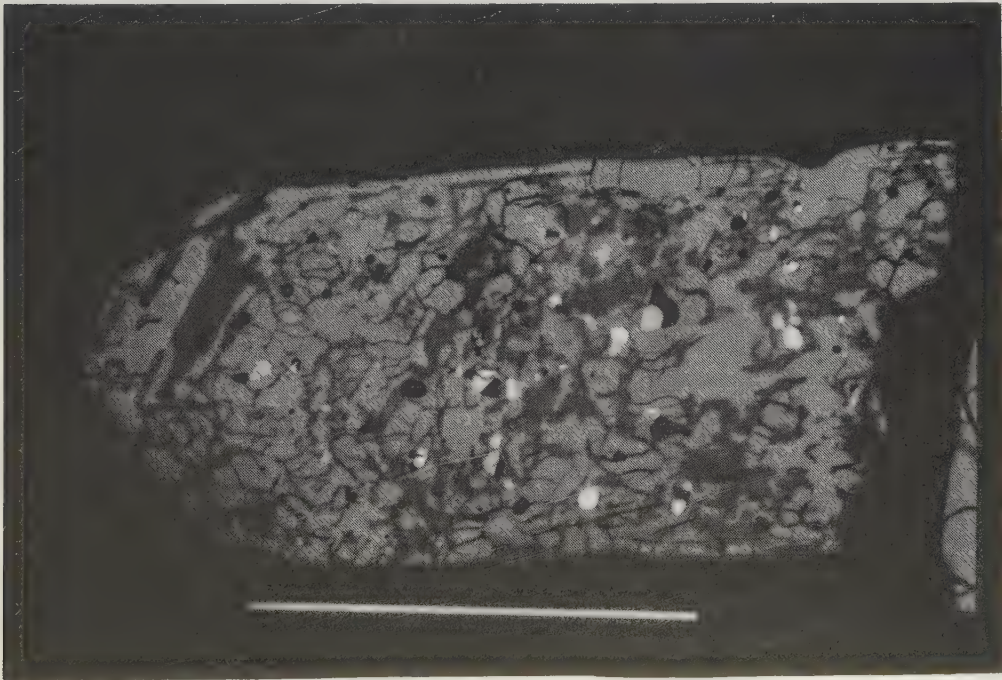


Fig. 5. Backscatter electron image of an altered zircon grain. Dark grey areas consist of altered, impure zircon ; the light grey areas are unaltered fresh zircon. Uraninite appears as white rounded dots. The length of the scale bar is 100 μm .

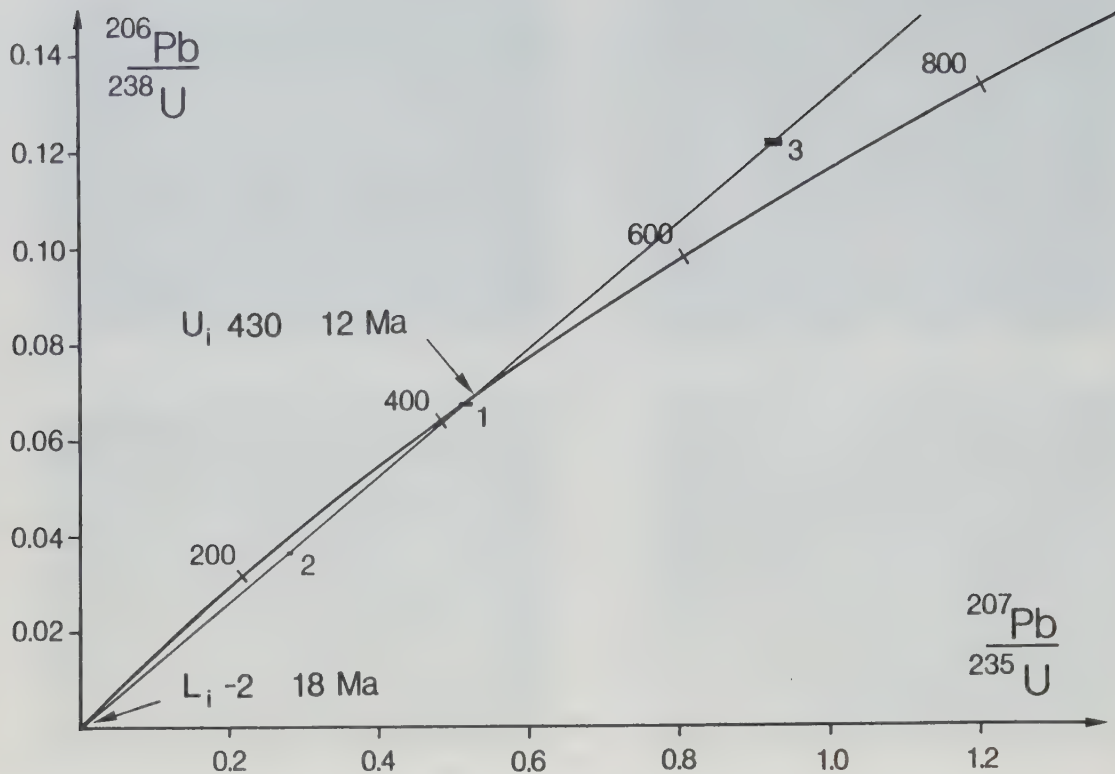


Fig. 6. Concordia diagram for the zircons of the Fossilia dyke. Symbol sizes correspond to an error of ± 2 sigma.

TNC in the Snåsa area, immediately to the east of the Vestranden region, where they have been described in detail by Andreasson & Johansson (1982). The reader is also referred to Nilsen (1971, 1978), Nilsen and Mukherjee (1972), and Guezou (1978) for descriptions of Gula rocks in Trondheim Region.

In the Gula Nappe of the Snåsa area (e.g. at Andorfjell; Andreasson & Johansson 1982), a feature of correlative significance is the rich variety and rapid alternation of rock types: mica schists, quartz-veined mica schists, amphibolites, hornblende gneisses, calc-silicate gneisses, magnesian marbles, graphitic schists and quartzites, felsites, small lenses of sulphide ore and garnetiferous sulphide ore, and trondhjemitic to granodioritic dykes. Most of these lithologies occur at Fossilia, but carbonates have not been found so far. The metavolcanic/metasedimentary ore association at Fossilia and Andorfjell have high Mn/Fe ratios in their silicate minerals and are very similar to the Gula "iron-formations" (Nilsen 1971). While trondhjemitic may occur in the Stören and Meråker Nappes, their main occurrence is in the Gula Nappe. According to Klingspor and Gee (1981), several generations of trondhjemitic with different relationships to deformation and metamorphism can be found in the Gula Nappe. Dykes of more granitic compositions also occur, often of pegmatoid character (David G. Gee, Uppsala; pers. comm. 1984). The trondhjemitic of the type area (Size 1979, p. 58) are tonalites (< 45 % modal quartz); subordinate granodiorites and monzodiorites also occur. Klingspor and Gee (1981, and in press) obtained a zircon age of 477 ± 7 Ma and Rb-Sr ages of 474 ± 23 ;

447 $\pm$ 47; 478 $\pm$ 37, 465 $\pm$ 13 Ma on trondhjemites from the Gula Nappe in the central Trondheim Region. These ages are somewhat older than the one obtained for the Fossilia dykes. However, due to the zircon overgrowths, the latter age is interpreted as a minimum age and the actual intrusion age of the Fossilia dykes may thus be in good agreement with the ages from central Trondheim region.

Conclusions

1. The lithological, structural and radiometric characteristics of the Fossilia cover rocks suggest their allochthonous nature. The lithologies can be correlated with the Gula lithologies of the Trondheim Region.
2. The Gula Nappe belongs to the Upper Allochthon of the Scandinavian Caledonides (Roberts & Gee 1985). In terms of terranes, the Gula rocks are of outboard affinity (Stephens & Gee 1985) and thus clearly exotic in their present setting which is "inboard" the Baltoscandian cratonic margin.
3. Amphibolite facies metamorphism and major deformation occurred after the intrusion of the dykes at c. 430 Ma, i.e. in Scandian time.
4. Our study demonstrates that basement-cover relationships can be interpreted in Vestranden despite tight isoclinal and recumbent folding and metamorphism of at least middle amphibolite facies conditions. With regard to terrane analysis, it appears possible to identify terranes and terrane boundaries also in areas where there was intense post-accretionary tectonometamorphism.

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PAPER VI

FORMATION OF SAPPHIRINE DURING RETROGRESSION OF A BASIC
HIGH PRESSURE GRANULITE, ROAN, VESTRANDEN, WESTERN GNEISS
REGION, NORWAY.

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FORMATION OF SAPPHIRINE DURING RETROGRESSION OF A BASIC HIGH-PRESSURE GRANULITE, ROAN, WESTERN GNEISS REGION, NORWAY.

L. Johansson and C. Möller

Abstract

Sapphirine-bearing rocks occur in the northern part of the Western Gneiss Region, Vestranden, central Norway. The sapphirine bearing rocks are characterized by a high $\text{MgO}/(\text{MgO}+\text{FeO})$ ratio, high Al_2O_3 , MgO and CaO , and low SiO_2 contents. These rocks form layers within larger complexes which originated as layered magmatic rocks. High PT-metamorphism produced a $\text{cpx} + \text{ky} + \text{gt}$ assemblage. The P and T estimates are $P = 14.5 \pm 2$ kbar and $T = 870 \pm 50$ °C. During retrogression, the high-P granulite assemblage broke down to form an intermediate-P granulite mineralogy comprising orthopyroxene, spinel, anorthite, sapphirine, corundum and plagioclase. Textural relationships suggest that sapphirine formed by the reaction: *spinel + kyanite* --> *sapphirine + corundum*, and probably also by a reaction between corundum, spinel and orthopyroxene. All reactions took place within the stability field of kyanite.

Textural and micro-chemical relationships indicate equilibrium conditions during the peak metamorphism, whereas pronounced disequilibrium characterizes the mineral associations formed during the early retrogression at low $P_{\text{H}_2\text{O}}$.

The investigation shows that parts of the northern segment of the Western Gneiss Region underwent a metamorphic evolution similar to the Caledonian one recorded from eclogite/granulite terrains further south.

Introduction

During field work in the Roan district in the westernmost part of Vestranden (Fig. 1), comparatively rare assemblages with sapphirine + corundum were discovered in metabasites. This mineral-pair was found in three outcrops along Brandsfjorden and one in Kråkfjord (Fig. 1).

Sapphirine typically occurs in rocks of granulite and uppermost amphibolite facies metamorphism. The host rocks have unusually high contents of Al_2O_3 and MgO , low SiO_2 content, and a high $\text{MgO} / (\text{MgO} + \text{FeO})$ ratio. Sapphirine bearing rocks have earlier been recorded from at least four places in Norway : at Grønøy, northern Norway (Östergaard 1969), at Tvedestrand, southern Norway (Touret & de la Roche 1971), at Vikeså, southwestern Norway (Hermans et al. 1976), and at Eiksunddal in the Western Gneiss Region (In Griffin & Mørk 1981).

The Roan coastal district is a part of the Vestranden gneiss area which forms the northern part of the Western Gneiss Region (Fig. 1). The Western Gneiss Region is the largest basement segment in the Scandinavian Caledonides. The

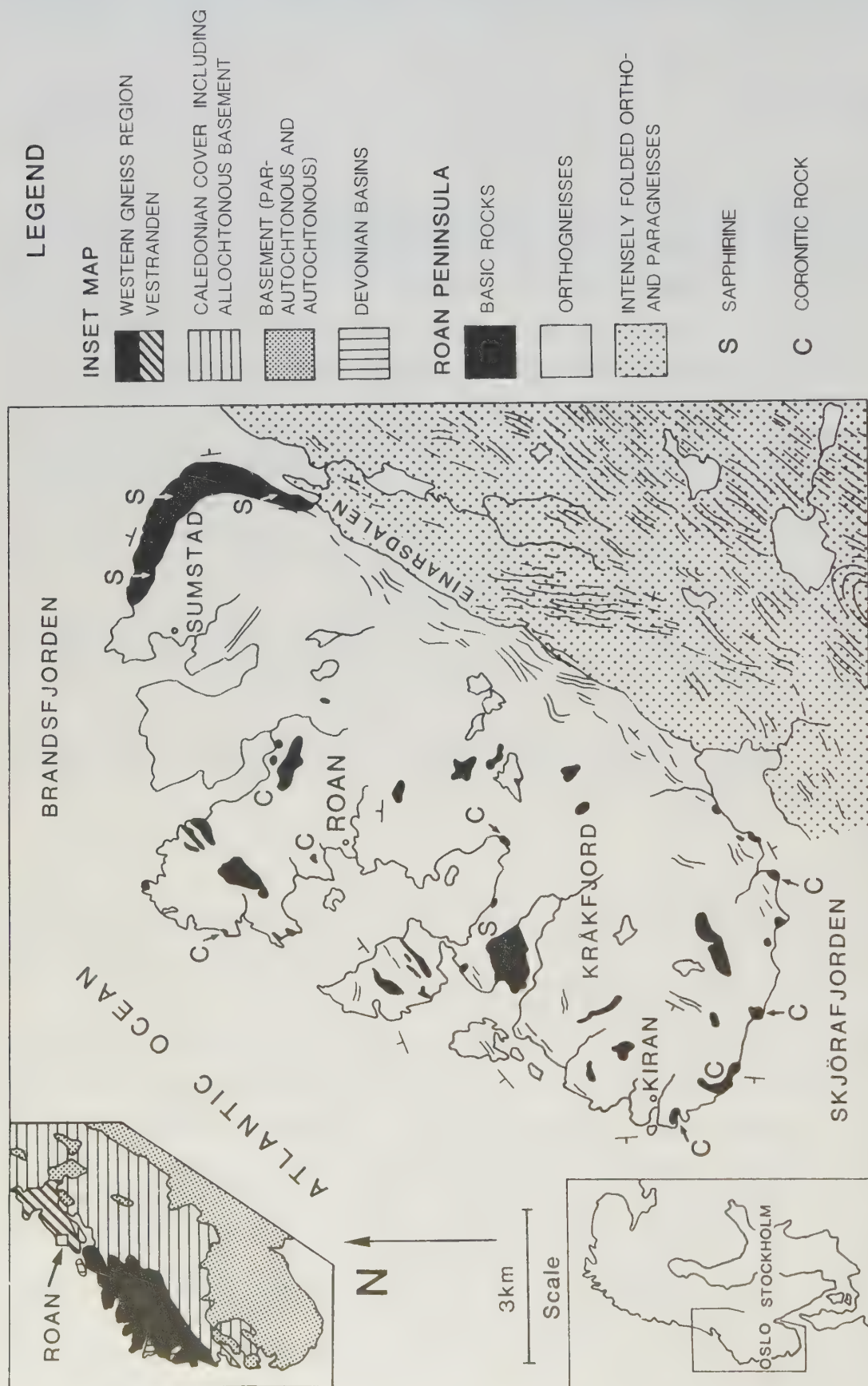


Fig. 1. Simplified geological map of the Roan peninsula, partly based on interpretation of aerial photographs. Generalized traces of regional foliation and the main directions of strike and dip are indicated. The upper inset figure shows the location of the Roan peninsula in the northern part of the Western Gneiss Region (Vestranden).

tectonics, metamorphic history and age relationships are complex, involving events during the Svecokarelian (2100-1750 Ma), Sveconorwegian (1250-850 Ma) and Caledonian (600-350 Ma) orogenies. Caledonian metamorphism led to the formation of high-pressure rocks from low-pressure protoliths (Griffin & Brueckner 1980; Griffin et al. 1985a). This high-pressure event has been interpreted as being related to the depression of the margin of the Baltic Shield (Western Gneiss Region) to great depths during Caledonian continent-continent collision. The rapid decompression terminating this high pressure event has been discussed by Krogh (1977, 1982), Bryhni et al. (1977), and Griffin et al. (1985a). However, granulite facies metamorphism predating the Caledonian metamorphism has also been recorded (Austrheim 1981; Austrheim & Griffin 1982, Griffin et al. 1985b). For details of the regional geology, metamorphism and age-relationships the reader is referred to papers by Andréasson & Gorbatshev (1980), Cuthbert et al. (1983), Gebauer (1983) and Griffin et al. (1985a).

This paper focusses on the mineralogical, petrographical, micro-textural and metamorphic relationships connected with the formation of sapphirine in the Kråkfjord metabasite and the implications of this event for interpretation of the PT-evolution of the westernmost part of Vestranden. The study of the Kråkfjord and Brandsfjord high-pressure granulites is also important since they occur in a gneiss terrain which is considered to be the basement beneath the Caledonian nappe pile. Therefore, timing of high-PT metamorphism, the peak PT-conditions and the tectonostratigraphic position of the Roan area are factors which must be taken into account in geological models which relates the basement to the nearby Caledonian nappes and the unmetamorphosed Devonian sedimentary rocks deposited on a high-grade basement in the Fosen area, 40 km south of Roan.

The main reasons for choosing the Kråkfjord rather than the Brandsfjord occurrences for a first study are good preservation of the rocks, the larger size of the locality and the absence of obvious country rock interactions. Hydrous phases occur in comparatively small amounts and were not involved in the sapphirine forming reactions. At the Brandsfjord occurrences, the sapphirine bearing rocks are more severely altered and retrogression is more intense. In some places H_2O , K_2O and CO_2 were introduced into the rocks.

The mineralogy, textures and bulk chemical compositions presented here are representative for the sapphirine bearing rock types of the Kråkfjord metabasite.

Geological setting and field relationships

The Roan peninsula is dominated by felsic and intermediate, often migmatitic orthogneisses. Metabasites are common and are found as lensoid bodies, fragmented dykes and boudins of all sizes from centimetres to hundreds of metres. In some of the metabasites, it is still possible to find subophitic textures. Remnants of primary magmatic pyroxenes are preserved, while plagioclase is recrystallized. Along the grain boundaries between the plagioclase domains and the magmatic pyroxenes, small garnets and pyroxenes are formed. Such garnet coronites with more or less

preserved primary igneous features are common along the southwestern coast of Vestranden. Occurrences of coronitic rocks in the Roan area are shown in Fig. 1.

Some metabasites have an amphibolite facies margin whereas the central parts show an intermediate to high-P granulite mineralogy with garnet and clinopyroxene, and often orthopyroxene, plagioclase and amphibole. The acid and intermediate gneisses commonly show amphibolite-facies mineralogy but locally garnet- and pyroxene-bearing assemblages are preserved.

The youngest rocks of the Roan area are pegmatites that cut most structures and have retrograded high-grade mineral assemblages. These intrusions postdate the formation of sapphirine and can probably be correlated with approximately 390 - 410 Ma old pegmatites (Pidgion & Råheim 1972; Johansson et al. in prep.) frequently found in the Western Gneiss Region.

The occurrence of primary magmatic textures and minerals in close proximity to high-P granulites in various stages of retrogression, is strong evidence for the lack of large-scale equilibrium during the peak of the high-grade metamorphism, as well as the uneven retrogression in the area.

The Kråkfjord metabasite is the largest (1000 x 500 m) and best preserved of at least four similar sapphirine-bearing metabasites in the Roan area (Fig. 1). Its central parts are relatively free of late amphibolitization and shearing. The Kråkfjord metabasite consists mainly of the sapphirine-bearing rock type. Distinct, concordant layers, bands and lenses (10 cm - 6 m thick) of other rock types of varying chemical/mineralogical composition occur throughout the basite. Most of these layers are basic to ultrabasic in composition and reflect a primary chemical variation. No clear stratification of mineral proportions can be seen within individual layers. A petrographic and chemical investigation including REE is in progress (Möller and Solyom in prep.). In this paper, only the sapphirine-bearing rock type will be considered.

In hand specimen, the sapphirine-bearing rock type consists of medium-grained clinopyroxene, kyanite and garnet in varying proportions. In certain mm - cm thick veinlets, generally discordant to the layering, clear, deep-blue kyanite crystals occur together with garnet, coarse-grained clinopyroxene, amphibole and plagioclase. The kyanites reach 3 cm in size.

A subordinate rock type, consisting of garnet, clinopyroxene and prismatic orthopyroxene, has been used in addition to the sapphirine-bearing rock type to estimate the PT- conditions. This rock type occur as a few dm thick, discrete layers within the sapphirine-bearing rock.

Bulk chemistry

Six analyses of sapphirine bearing rocks are shown in Table 1. The analyses were made by X-ray fluorescence spectrometry and atomic absorption spectrometry at the Geochemical Laboratory of the Department of Geology, University of Lund, using analytical techniques described by Solyom et al. (1984). In samples R-1 to R-3, which represent the hand specimens from which most thin sections were made, MnO, MgO, Na₂O, P₂O₅ and the trace elements Cr, Ni, Cu, Zn

TABLE 1

Sample	KR 1	KR 2	KR 3	R 1	R 2	R3
SiO ₂ (wt-%)	46.79	46.05	47.65	46.07	47.68	48.89
TiO ₂	0.15	0.15	0.11	0.12	0.14	0.32
Al ₂ O ₃	17.18	17.28	16.54	19.90	18.74	13.05
Fe ₂ O ₃	0.77	0.76	0.76	0.77	0.85	0.82
FeO	6.45	7.52	3.64	5.14	3.61	5.84
MnO	0.12	0.14	0.09	0.10	0.08	0.12
MgO	13.52	13.90	12.04	13.40	10.80	13.40
CaO	12.13	12.00	16.63	12.41	15.30	14.53
Na ₂ O	1.63	1.21	1.15	1.11	1.73	1.71
K ₂ O	0.16	0.07	0.05	0.08	0.09	0.06
P ₂ O ₅	0.02	0.02	0.02	0.17	0.18	-----
L.O.I	0.92	1.04	0.82	0.81	0.75	0.99
TOTAL	99.84	100.14	99.50	100.08	99.95	99.73

Trace element
in ppm.

Cr	1138	1164	2175	668	1210	2460
Ni	n.a.	n.a.	n.a.	306	224	218
Cu	n.a.	n.a.	n.a.	18	70	69
S	n.a.	n.a.	n.a.	454	701	878
Zn	n.a.	n.a.	n.a.	52	41	48

MgO						
MgO + FeO	0.68	0.65	0.77	0.72	0.75	0.70
(wt-%)						

and S were determined by proton-induced X-ray / gamma emission spectrography (PIXE-PIGE) at the Department of Nuclear Physics of the Lund Institute of Technology employing methods described by Carlsson & Akselsson (1981) and Carlsson (1984).

The most notable features seen in Table 1 are the relatively high Mg/(Mg+Fe²⁺) ratios (0.77-0.86) and amounts of CaO, Al₂O₃ and Cr. Due to the high content of Al, the rocks are high in normative plagioclase (41-58 wt-%). They have 14-26 wt-% normative olivine and 9-35 wt-% normative clinopyroxene. With

respect to silica they are undersaturated and either slightly nepheline-normative or hypersthene-normative (Table 2). The low Al_2O_3 content in R-3 reflects a low content of modal kyanite.

The field relationships together with the major and trace element chemistry suggest an igneous origin for the rocks. A probable explanation for the high MgO , Al_2O_3 , CaO and Cr contents is that the sapphirine-bearing rocks were cumulates of olivine, clinopyroxene, spinel and anorthite-rich plagioclase. The contents of Ni and Cr indicate the presence of olivine and spinel and/or clinopyroxene, respectively.

TABLE 2. CIPW-norms for sapphirine-bearing rocks in the Kråkfjord metabasite.

CIPW norm (wt-%)	KR 1	KR 2	KR 3	R 1	R 2	R 3
Or	0.95	0.39	0.28	0.56	0.53	0.56
Ab	13.78	10.22	8.41	9.43	12.52	13.49
An	39.03	41.48	39.81	48.98	43.19	28.09
Cpx	16.88	14.46	33.81	9.44	25.06	35.30
Opx	1.24	5.79	-----	7.99	-----	-----
Ol	25.59	25.33	14.34	21.15	14.94	18.70
Mt	1.11	1.09	1.11	1.16	1.23	1.16
Il	0.29	0.29	0.21	0.30	0.27	0.61
Ap	0.03	0.03	0.03	0.31	0.39	-----
An/An+Ab	0.73	0.79	0.82	0.83	0.76	0.66
Molar.prop. $\text{Mg}/\text{Mg}+\text{Fe}^{2+}$	0.79	0.77	0.86	0.83	0.84	0.81

Petrography and mineral chemistry

The minerals in the sapphirine-bearing rock type can be divided into two groups on the basis of textures. The *initial metamorphic assemblage* comprises medium-grained crystals of clinopyroxene, kyanite and garnet. Accessory minerals are rutile, apatite and Cu-Fe-sulphides. Along the margins of these initial metamorphic assemblage minerals a *secondary metamorphic assemblage* has formed, which consists of very fine grained, often symplectitic orthopyroxene, spinel, plagioclase, sapphirine, corundum, Cr-spinel and locally amphibole and magnetite. Compositional differences in the secondary minerals even over short distances, a marked zoning of plagioclase and 'frozen' reactions preserved in symplectites around garnet and clinopyroxene show that chemical and textural equilibrium prevailed only over very short distances (Fig. 2).

The mineral analyses were made with energy-dispersive X-ray equipment (EDX-"microprobe") at the Department of Geology, University of Lund. Mineral standards were used and ZAF corrections were applied with the KEVEX computer programme MAGIC V. All Fe is calculated as FeO. Mineral chemistry is shown in tables and in Fig. 3.

The abbreviations for minerals and end-member compositions in the text, figures and tables are: *Pl* = plagioclase, *And* = andesine, *An* = anorthite, *Co* = corundum, *Cpx* = clinopyroxene, *Cr-spi* = chrome-rich spinel, *Gt* = garnet, *Hbl* = hornblende, *Ky* = kyanite, *Opx* = orthopyroxene, *Sa* = sapphirine, *Spi* = Fe-Mg-Al spinel, *Pyr* = pyrope, *Alm* = almandine, *Gro* = grossular, *Adr* = Andradite, *Sp* = spessartine, *Jd* = jadeite, *Di* = diopside, *Hd* = hedenbergite, *Ts* = tschermaks molecule, *Fs* = ferrosillite, *En* = enstatite

Garnet.

The amount of garnet is highly variable. Garnets sometimes make up more than 50 vol-% of the rock. Individual garnet grains are usually anhedral and about 0.5 mm across. Their irregular shape is the result of breakdown and replacement by anorthite - orthopyroxene - spinel symplectite (Figs. 2, 5). The garnets are free of inclusions and show no chemical zoning. Exceptions are the outermost, 1-5 microns thick margins of some reacting garnets, which are enriched in Fe. The thin, light grey rim seen in electron backscatter images of garnets e.g. in Fig. 5 is due to Fe-enrichment. Fe were in some cases expelled as minute magnetite grains in the symplectites around garnets. A typical garnet composition is:



The $\text{Mg}/(\text{Mg} + \text{Fe}^{2+})$ ratios are 0.64-0.68.

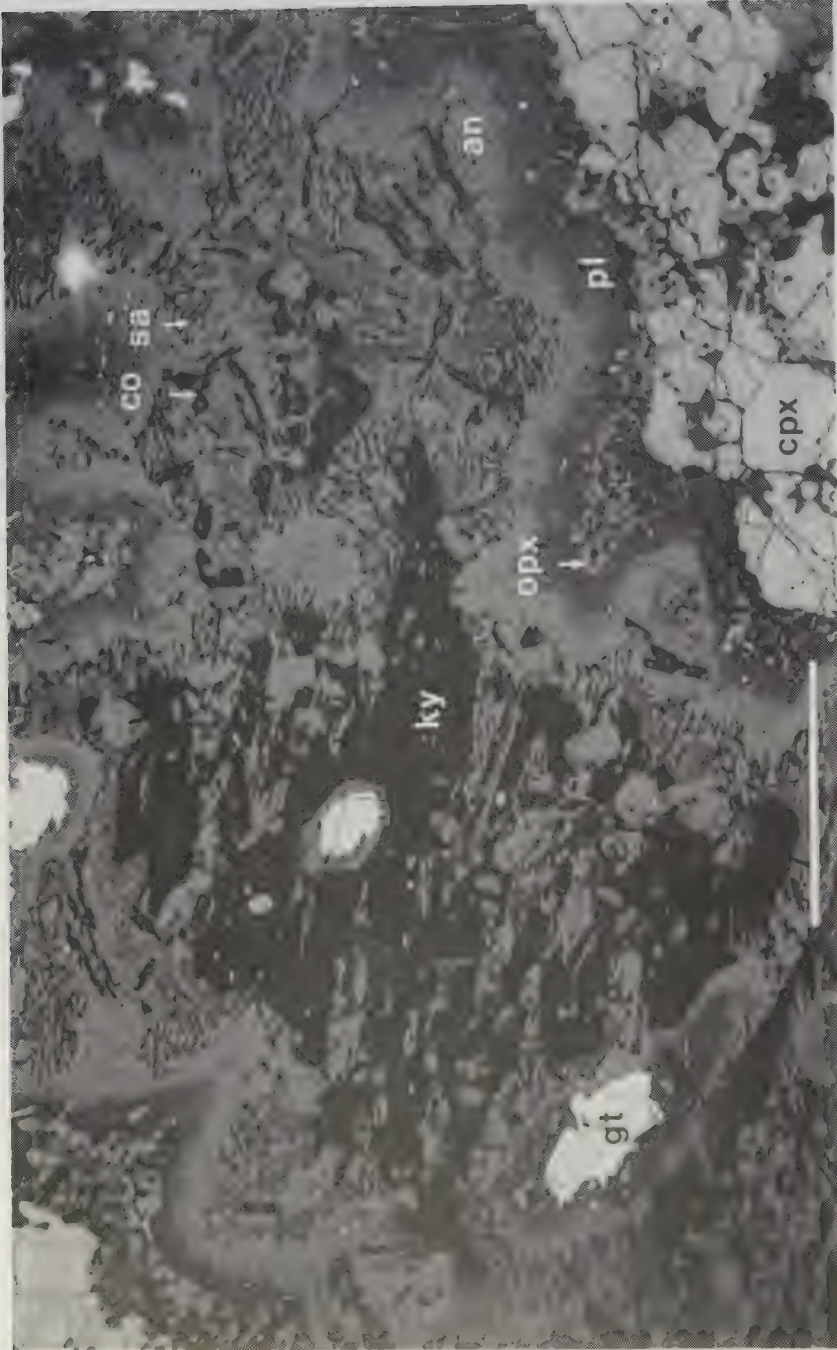


Fig. 2. Typical reaction domain around strongly corroded kyanite which is partly replaced by a network of corundum, sapphirine and anorthite. Note the irregular shaped remnants of garnets and the marked zoning of the plagioclase domains. Backscatter electron image. Scale bar = 1000 microns. Abbreviations as in the text (p.7).

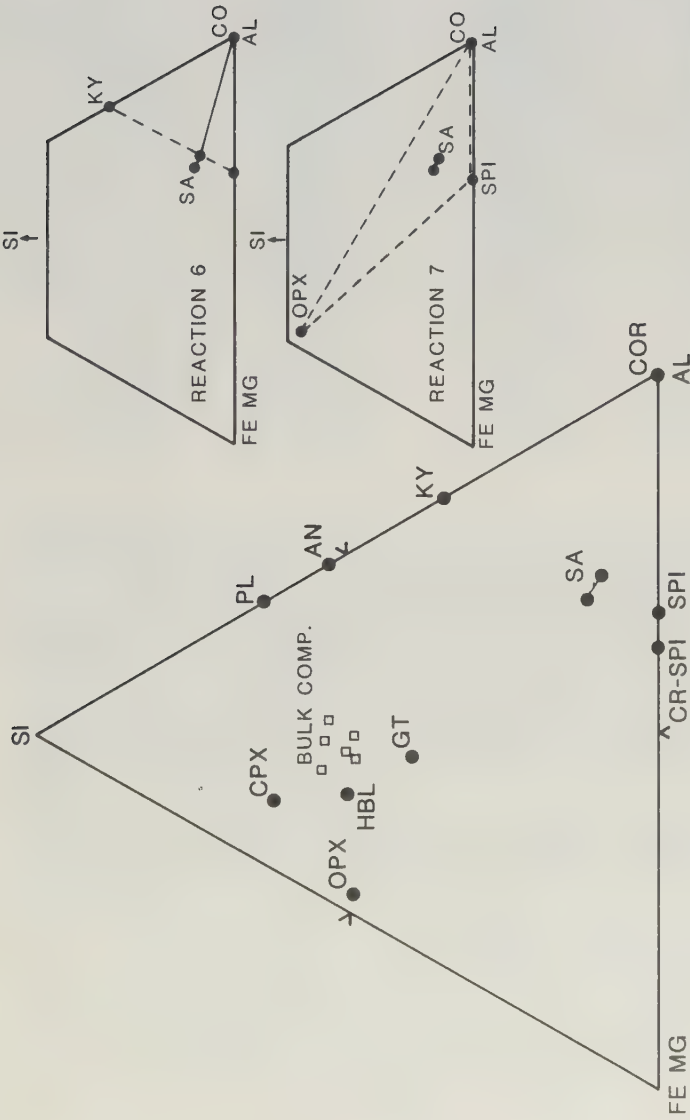


Fig. 3a. Mineral compositions and bulk compositions plotted in the Si - (Mg Fe) - Al (mole-%) triangle. Abbreviations as in the text (p. 7).
b: Graphical presentation of reaction (6).
c: Graphical presentation of reaction (7).

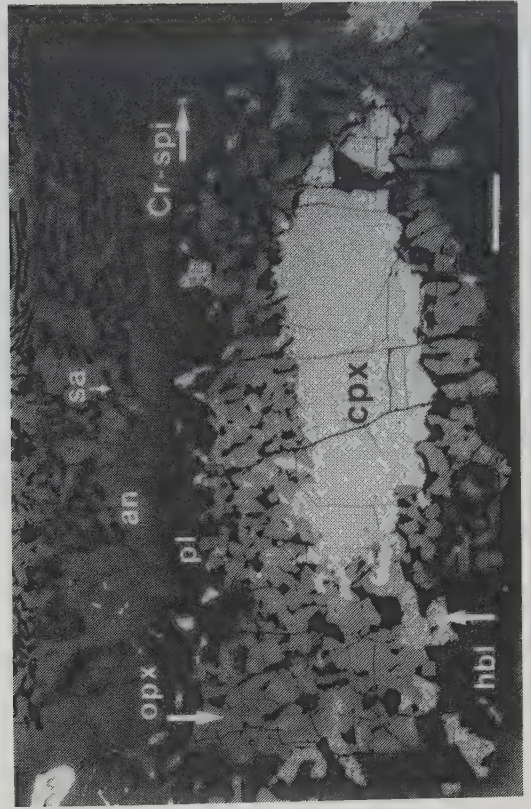


Fig. 4. Plagioclase - orthopyroxene rim around clinopyroxene. Note the marked zoning of the plagioclase. Backscatter electron image. Scale bar = 100 microns. Abbreviations as in the text (p. 7).

VI- 10

GARNET

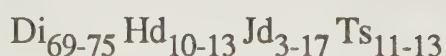
(wt-%)	GT 1	GT 2	GT 3	GT 4	GT 5
SiO ₂	40.70	41.52	41.11	41.31	41.25
Al ₂ O ₃	22.74	23.01	22.72	22.66	23.39
FeO	14.07	13.17	14.17	14.03	14.96
MgO	14.94	14.93	14.94	15.34	15.01
CaO	6.83	7.58	7.06	6.54	6.02
MnO	0.47	0.35	0.35	0.37	0.34
Total	99.75	100.56	100.36	100.26	100.98

Formula based on 12 oxygens:

Si	2.99	3.01	3.00	3.01	2.99
Al	1.97	1.97	1.96	1.95	2.00
Fe ³⁺	0.04	0.03	0.04	0.05	0.01
Fe ²⁺	0.82	0.77	0.83	0.81	0.90
Mg	1.63	1.61	1.63	1.67	1.62
Ca	0.54	0.59	0.55	0.51	0.47
Mn	0.03	0.02	0.02	0.02	0.02
Total	7.99	7.98	8.01	8.00	7.99
Mg/Mg+Fe ²⁺	0.67	0.68	0.66	0.67	0.64

Clinopyroxene

Prismatic light green clinopyroxene makes up more than 50 vol-% of the rock. Rutile, quartz, amphibole and plagioclase occur as inclusions in the clinopyroxenes, some regularly distributed along crystallographic planes, others as irregular blebs. The proportion of irregularly shaped plagioclase and amphibole inclusions increases with the degree of retrogression. Therefore, these phases probably represent a secondary retrograde assemblage. Usually, the clinopyroxenes are surrounded by a rim of orthopyroxene and plagioclase with or without amphibole symplectite (Fig. 4). Clinopyroxenes are diopsides with varying jadeite contents and no chemical zoning was found. A typical clinopyroxene composition is:



The Mg/(Mg+Fe²⁺) ratios are 0.87-0.90.

CLINOPYROXENES

(wt-%)	CPX 1	CPX 2	CPX 3	CPX 4	CPX 5
SiO ₂	52.40	51.63	51.07	51.44	51.84
Al ₂ O ₃	6.60	5.81	7.31	8.19	5.71
Cr ₂ O ₃	-----	0.36	0.34	-----	-----
FeO	3.27	3.61	3.67	3.33	3.09
MgO	14.71	14.78	14.12	13.30	14.73
CaO	23.04	22.73	22.12	20.75	22.65
Na ₂ O	0.65	0.40	1.16	2.19	1.05
Total	100.67	99.32	99.79	99.20	99.07

Formula based on 6 oxygens

Si	1.89	1.89	1.86	1.88	1.90
Al	0.28	0.25	0.31	0.35	0.25
Cr	-----	0.01	0.01	-----	-----
Fe ²⁺	0.10	0.11	0.11	0.10	0.09
Mg	0.79	0.81	0.77	0.72	0.81
Ca	0.89	0.89	0.87	0.81	0.89
Na	0.05	0.03	0.08	0.16	0.07
Total	4.00	3.99	4.01	4.02	4.01

Mg/Mg+Fe ²⁺	0.89	0.88	0.87	0.88	0.90
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Sapphirine:

The sapphirine is generally confined to domains around kyanite where it is found as fine-grained, colourless to pale green-blue elongated crystals which together with idioblastic corundum form a network in plagioclase around the kyanite. The sapphirine and corundum are often intimately associated with small Cr-spinels. Sapphirine nucleates directly on kyanite (Fig. 7) and forms narrow rims along the kyanite edges. Preferred growth of sapphirine is sometimes seen along the (100)-planes of kyanite.

In a few places, spinel is found outside the garnet breakdown symplectite. When it occurs close to kyanite, it is often rimmed by sapphirine (Fig. 8). Rarely, sapphirine is seen replacing orthopyroxene and spinel around garnet (Fig. 9). In one case, sapphirine has been found selectively replacing the spinel within the symplectitic orthopyroxene (Fig. 10). Grains of corundum or the association corundum and spinel are in places rimmed by sapphirine (Fig. 11).

In the system SiO₂ - (Mg,Fe²⁺)O - (Al,Fe³⁺,Cr)₂O₃ (Fig.12), natural

sapphirines fall on or close to the line representing the coupled substitution $\text{Mg} + \text{Si} \leftrightarrow 2 \text{Al}$, and mostly have compositions between $2 \text{MgO} \cdot 2 \text{Al}_2\text{O}_3 \cdot 1 \text{SiO}_2$ (2:2:1) and $7 \text{MgO} \cdot 9 \text{Al}_2\text{O}_3 \cdot 3 \text{SiO}_2$ (7:9:3) (Higgins et al. 1979). Fe^{3+} was calculated according to the method of Higgins et al. (1979). The compositions of Kråkfjord sapphirines are variable, but most are slightly more aluminous than the 7:9:3 composition, and can be called peraluminous (Schreyer & Abraham 1975). All contain minor amounts of Cr. The highest Cr_2O_3 contents (1.87 wt-%) are found in grains in contact with Cr-spinel. The $\text{Mg}/(\text{Mg}+\text{Fe}^{2+})$ ratios are 0.88 - 0.91. Very thin light-grey margins on individual sapphirine grains can be seen in Fig. 7. However, no chemical zoning was detected across the margins of the sapphirine grains.

SAPPHIRINES

(wt-%)	SA 1	SA 2	SA 3	SA 4	SA 5
MgO	17.18	16.83	16.84	17.17	17.62
Al_2O_3	67.67	67.39	67.13	66.52	66.23
SiO_2	11.32	11.28	11.63	11.91	12.01
Cr_2O_3	0.63	0.18	0.90	0.89	0.89
FeO	4.04	4.11	4.13	4.02	4.25
Total	100.84	99.79	100.63	100.51	101.00

Formula based on 20 oxygens.

Al	9.27	9.32	9.22	9.15	9.08
Si	1.32	1.32	1.36	1.39	1.40
Mg	2.98	2.94	2.93	2.98	3.05
Fe^{2+}	0.36	0.39	0.40	0.38	0.37
Fe^{3+}	0.04	0.02	-----	0.01	0.05
Cr	0.06	0.02	0.08	0.08	0.08
Total	14.03	14.01	13.99	13.99	14.03
$\text{Mg}/(\text{Mg}+\text{Fe}^{2+})$	0.89	0.88	0.88	0.89	0.89

SAPPHIRINES cont.

(wt-%)	SA 6	SA 7	SA 8	SA 9	SA 10
MgO	18.16	17.48	18.44	17.97	18.47
Al ₂ O ₃	66.03	65.79	64.73	64.38	64.25
SiO ₂	12.24	12.40	12.94	12.97	13.44
Cr ₂ O ₃	0.32	0.39	0.24	0.52	0.52
FeO	4.01	4.33	4.35	4.39	4.23
Total	100.76	100.39	100.70	100.23	100.91

Formula based on 20 oxygens

Al	9.05	9.06	8.89	8.88	8.80
Si	1.42	1.45	1.51	1.52	1.56
Mg	3.15	3.04	3.20	3.14	3.19
Fe ²⁺	0.31	0.41	0.42	0.40	0.38
Fe ³⁺	0.08	0.01	-----	0.03	0.03
Cr	0.03	0.04	0.02	0.05	0.05
Total	14.04	14.01	14.04	14.02	14.01
Mg/Mg+Fe ²⁺	0.91	0.88	0.88	0.89	0.89

Orthopyroxene.

Orthopyroxenes occur exclusively in the symplectitic rims around garnets and clinopyroxenes. They are bronzites with Fs₁₅₋₁₆. The contents of Al₂O₃ in orthopyroxenes formed by garnet breakdown range from 3.93 to 5.46 wt-%. In those rimming clinopyroxenes Al₂O₃ is 1.62 to 4.14 wt-%. Small amounts of CaO and Cr₂O₃ are usually present. The occurrence of orthopyroxene in the secondary metamorphic assemblage is characteristic of the Kråkfjord sapphirine-bearing rocks. Elsewhere in the Kråkfjord complex, orthopyroxene is part of the initial metamorphic assemblage together with clinopyroxene and garnet.

Corundum.

Elongated, idiomorphic corundum crystals occur scattered within the sapphirine domains (Fig. 2). Rarely, corundum grows directly at the expense of kyanite (Fig. 13). The modal ratio corundum/sapphirine is variable. The corundum

is almost pure Al_2O_3 with small amounts of Fe_2O_3 and Cr_2O_3 . In hand specimen, the corundum is sometimes intensely red, which is probably due to the Cr_2O_3 content.

ORTHOPYROXENES AND CORUNDUM

OPGT = orthopyroxene in symplectite around garnet. OPCP = orthopyroxene in symplectite around clinopyroxene.

(wt-%)	OPGT 1	OPGT 2	OPCP1	OPCP 2	CO
SiO_2	53.71	53.39	56.06	56.01	-----
Al_2O_3	4.66	5.26	2.52	2.73	99.45
Cr_2O_3	0.40	0.55	0.37	-----	0.46
FeO	10.07	10.17	10.56	11.08	0.30
MgO	30.27	30.23	31.06	30.89	-----
CaO	0.25	0.24	0.27	0.29	-----
Total	99.36	99.80	100.85	101.00	100.21
Si	1.90	1.88	1.95	1.95	-----
Al	0.19	0.22	0.10	0.11	1.99
Cr	0.01	0.01	0.01	-----	0.01
Fe^{2+}	0.30	0.30	0.31	0.32	< 0.01
Mg	1.59	1.59	1.61	1.60	-----
Ca	0.01	0.01	0.01	0.01	-----
Total	4.00	4.01	3.99	3.99	2.00
$\text{Mg}/\text{Mg}+\text{Fe}^{2+}$	0.84	0.84	0.84	0.84	-----
N:o oxygens in formula	6	6	6	6	3

Spinel.

Very fine grained (< 10 micron) spinel crystals form a symplectite with orthopyroxene replacing garnet (Fig.5). Spinel is seldom found outside the symplectites. Compositionally it is Mg-Fe-Al spinel with approximately 45 % hercynite. Minor amounts of Cr_2O_3 are sometimes present. Only a few grains were large enough for microprobe analysis.

Cr-spinel.

In most plagioclase domains, there occur small (< 10 micron), often vermicular Cr-spinels (Fig.4). Due to their small size, they are very difficult to analyse, but their composition has been found to vary even over distances of less than a millimetre. These spinels are completely different from those found in the symplectites. Considerable amounts of Cr substitute for Al (0.2 - 0.5 atoms in a formula based on 4 oxygens). The highest Cr_2O_3 -content recorded is 35 wt-%. Zn is commonly present.

Amphibole.

Greenish to brownish amphibole occurs sparsely intergrown with the clinopyroxenes, or enters the orthopyroxene-plagioclase symplectite around clinopyroxene and garnet. The amount of amphibole is variable; many samples almost completely lack amphiboles. Using the classification scheme of Leake (1978), the analyses plot in the low-silica part of the magnesio-hornblende field. The $\text{Mg}/(\text{Mg}+\text{Fe}^{2+})$ ratios are 0.86 - 0.87.

Kyanite.

Blue kyanite crystals are evenly distributed in the rock. Most of these are partly replaced by anorthite, corundum and sapphirine. The remaining kyanites are strongly corroded (Fig. 2) and have irregular shapes. Inclusions of garnet, rutile and opaques occur in the kyanite. Well preserved, up to 30 mm long, deep blue, often clear kyanite crystals are found in thin veinlets. Chemically the kyanite is almost pure Al_2SiO_5 with minor amounts of Fe_2O_3 and Cr_2O_3 .

Plagioclase.

Plagioclase occurs in a granoblastic mass separating kyanites from clinopyroxene and garnet. The plagioclase domains between kyanite and clinopyroxene are characteristically zoned (Figs. 2, 4). A compositional profile (Fig. 6) across a plagioclase domain shows anorthite content decreasing towards the clinopyroxene (An_{92} to An_{50}) with an abrupt decrease at the 'andesine-front'. This 'front' cuts through individual grains and is thus not limited by grain boundaries.

SPINEL, CR-SPINEL, HORNBLLENDE AND KYANITE

(wt-%)	SPI-S ^a	CRSPI-1	CRSPI-2	HBL 1	HBL 2	KY
SiO ₂	-----	-----	-----	48.33	46.09	37.35
TiO ₂	-----	-----	-----	0.50	0.45	-----
Al ₂ O ₃	66.28	44.43	53.50	12.51	12.73	62.12
Cr ₂ O ₃	0.66	20.91	9.62	0.52	0.18	0.37
FeO	20.20	20.59	22.46	4.90	5.23	0.16
MgO	15.23	12.77	13.78	18.33	18.74	-----
CaO	-----	-----	-----	12.24	12.17	-----
MnO	-----	-----	-----	-----	0.12	-----
Na ₂ O	-----	-----	-----	1.26	1.13	-----
K ₂ O	-----	-----	-----	0.16	0.24	-----
Total	102.37	100.06	99.35	98.74	97.08	100.00
Formula						
Si	-----	-----	-----	6.70	6.53	1.00
Ti	-----	-----	-----	0.05	0.05	-----
Al	1.98	1.49	1.73	2.04	2.13	1.98
Cr	0.01	0.47	0.21	0.06	0.02	0.01
Fe ²⁺	0.43	0.49	0.52	0.57	0.62	< 0.01
Mg	0.58	0.54	0.57	3.78	3.96	-----
Ca	-----	-----	-----	1.82	1.85	-----
Mn	-----	-----	-----	-----	0.01	-----
Na	-----	-----	-----	0.34	0.31	-----
Total	3.00	2.99	3.03	15.39	15.52	3.00
Mg/Mg+Fe ²⁺	0.57	0.52	0.52	0.87	0.86	-----
N:o of oxygens						
in formula	4	4	4	23	23	5

a : SPI-S = spinel in symplectite around garnet.

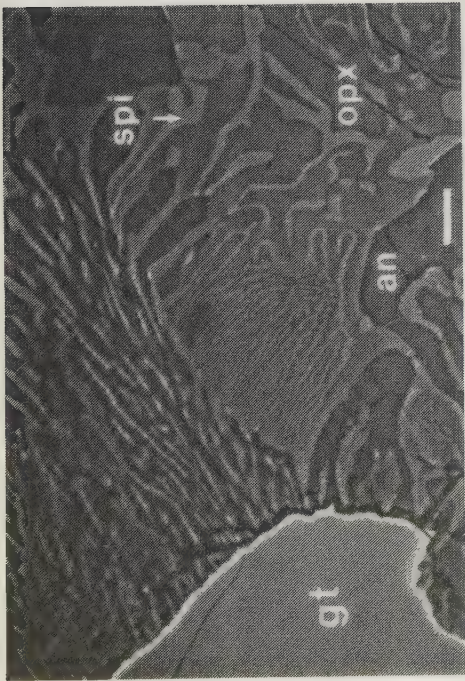


Fig. 5. Breakdown of garnet to anorthite, orthopyroxene and spinel. Note the decreasing grain size of spinel towards the garnet rim. Backscatter electron image. Scale bar = 10 microns. Abbreviations as in the text (p. 7).

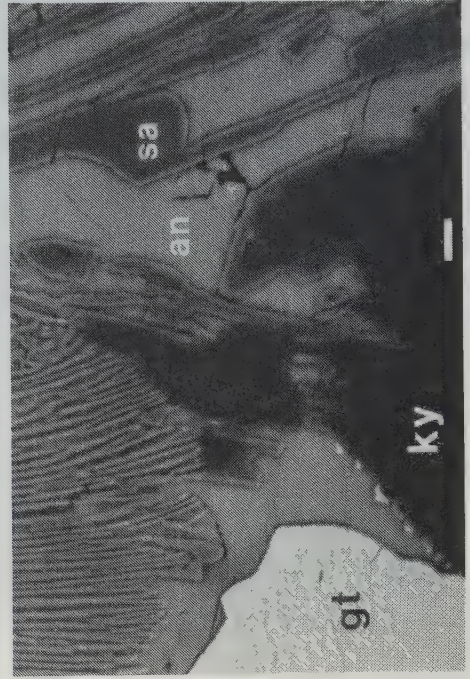
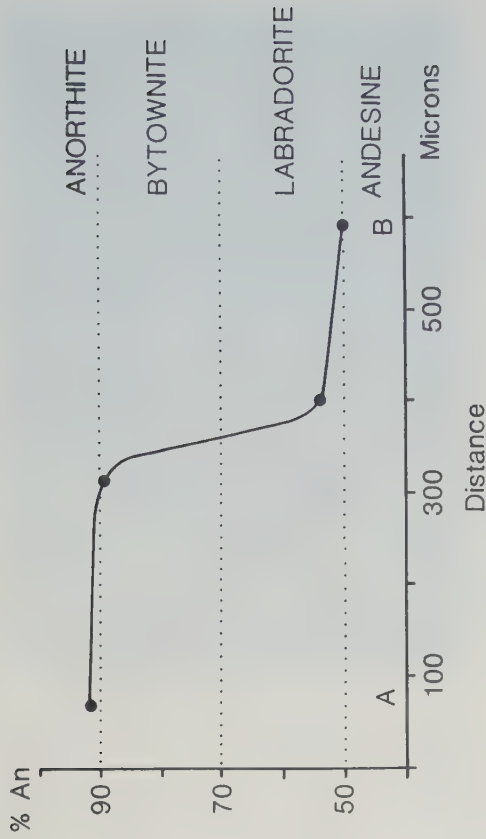


Fig. 6. Compositional zoning of plagioclase between a sapphirine domain (A) and a clinopyroxene (B).
Fig. 7. Sapphirine growth along the margins of kyanite. Scale bar = 10 microns. Backscatter electron image. Abbreviations as in the text (p. 7).

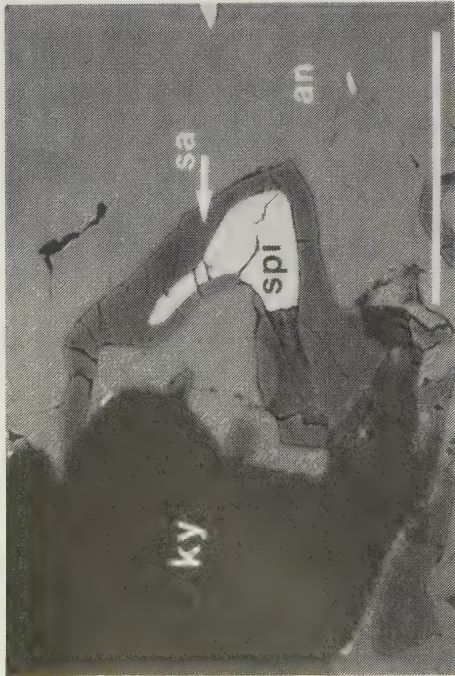
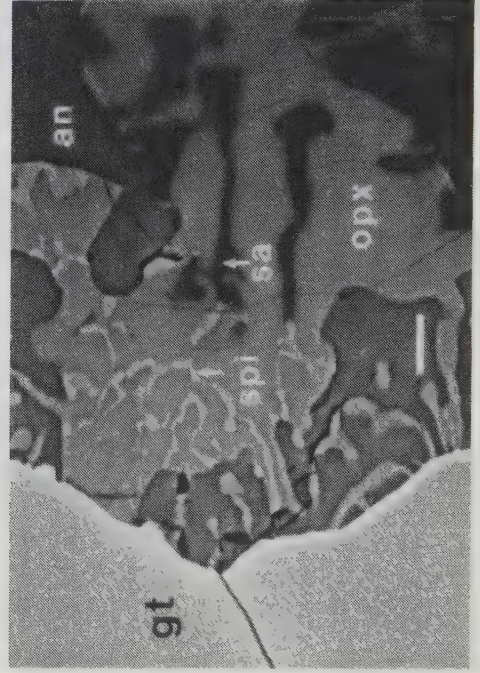
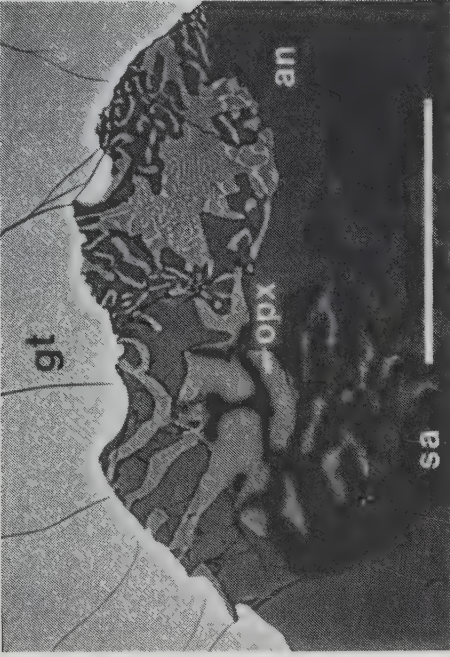


Fig. 8. Sapphire replacing spinel and kyanite. Backscatter electron image. Scale bar = 100 microns. Abbreviations as in the text (p. 7).

Fig. 9. Sapphire replacing spinel and orthopyroxene. Note the tiny remnants of orthopyroxene within the sapphire and the way sapphire follows spinel lamellae (c.f. Fig. 10). Backscatter electron image. Scale bar = 100 microns. Abbreviations as in the text (p. 7).

Fig. 10. Selective replacement of spinel by sapphire within orthopyroxene - spinel symplectite. Backscatter electron image. Scale bar = 10 microns. Abbreviations as in the text (p. 7).



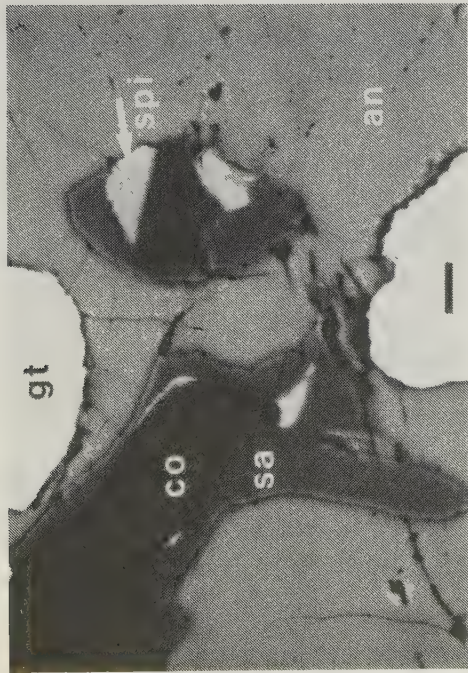


Fig. 11. Sapphire replacing spinel and corundum. Backscatter electron image. Scale bar = 10 micron. Abbreviations as in the text (p. 7).

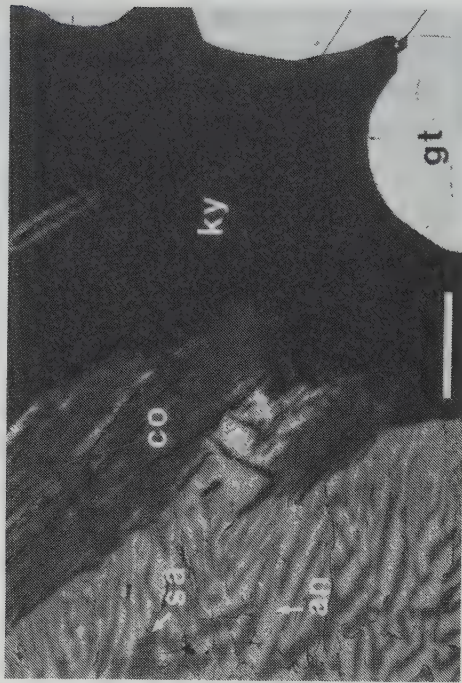
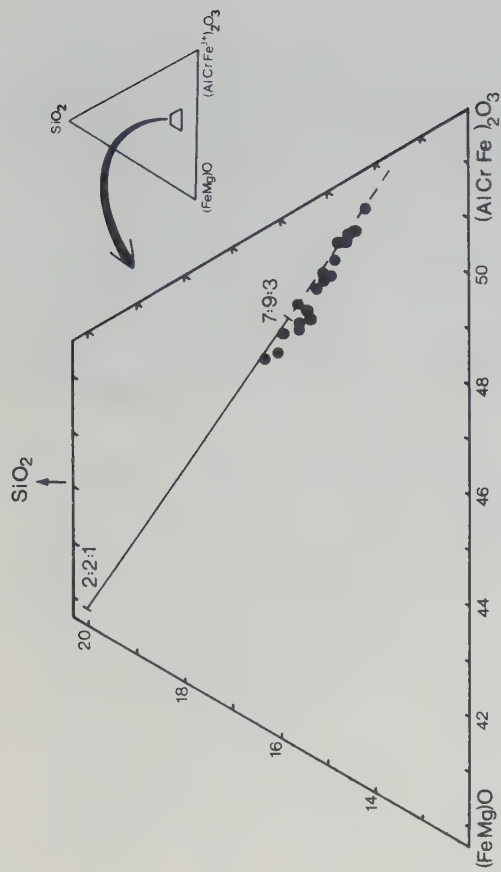


Fig. 12. Composition of sapphire shown in the SiO₂ - (Fe,Mg)O - (Al^{VI}CrFe³⁺)₂O₃ system. The line indicates the substitution Mg + Si <---> 2 Al.

Fig. 13. Corundum, anorthite and sapphire replacing kyanite. Note the absence of reaction between the garnet and the kyanite. Backscatter electron image. Scale bar = 100 microns. Abbreviations as in the text (p. 7).

P T estimates

Eleven garnet - clinopyroxene pairs and nine garnet - orthopyroxene pairs were used to estimate the temperature and pressure of formation of the initial metamorphic assemblages clinopyroxene + kyanite + garnet and orthopyroxene + clinopyroxene + garnet. The latter assemblage occurs as a layer within the kyanite-rich rock. Both these assemblages represent equilibrium conditions at or close to the metamorphic maximum (highest P and T). Geobarometry is based on alumina solubility in orthopyroxene coexisting with garnet (Harley & Green 1982 and Harley 1984). The temperature estimates are based on the Fe-Mg exchange between garnet and clinopyroxene (Ellis & Green 1979) and between garnet and orthopyroxene (Sen & Battacharaya 1984).

We have also tried to estimate temperatures and pressures for the formation of the secondary symplectitic minerals around garnet (reaction 1) and clinopyroxene (reaction 4). Temperatures for the latter reaction were estimated by using the thermometer based on the two pyroxene solvus (Wells 1977), assuming equilibrium conditions very close (< 15 microns) to the grain boundaries. The temperatures obtained for the garnet breakdown reaction are unrealistically high, around 1000°C , and pressures too low, less than 5 kbar. This is probably due to the presence of extremely fine grained (< 1 micron) spinel as a symplectitic intergrowth within the orthopyroxene. This is illustrated by Fig. 5 where the grain size decreases towards the garnet. Close to the garnet the spinel phase no longer can be resolved by the electron microscope. However, the presence of spinel in the orthopyroxene is indicated by the relatively high alumina content (around 6 wt-% Al_2O_3) in the symplectitic orthopyroxene close to the garnet.

All analyses were made on unzoned grains with 'clean', straight grain boundaries between the coexisting minerals. All grains showing signs of secondary adjustments such as dentate grain boundaries and minute intra-grain boundary mineral phases were avoided. The distance between analysed points is less than 30 microns. Corrections for Fe^{3+} in garnets and pyroxenes were made by the method of Ryburn et al. (1976).

The results presented in Table 3 are valid for the rocks at Kråkfjord. Garnet - orthopyroxene pairs suggest that these rocks had equilibrated at $T = 880 \pm 60^{\circ}\text{C}$ and $P = 14.5 \pm 2$ kbar. Based on the discussion of Harley (1984) we consider the barometer of Harley & Green (1982) to be the one most suitable for the Kråkfjord rocks of the two barometers used here. The temperature obtained by the thermometer of Sen & Bhattacharaya (1984) is *independently* confirmed by the garnet - clinopyroxene equilibrium (Ellis & Green 1979) which yields $T = 870 \pm 50^{\circ}\text{C}$ at $P = 14.5$ kbar.

The two-pyroxene T-estimates suggest temperatures around 700°C for the formation of the orthopyroxene - plagioclase symplectite around clinopyroxene. Unfortunately, no pressure estimate can be made for this reaction.

Table 3.

9 Garnet - orthopyroxene (initial metamorphic mineral assemblage) pressure estimates in kbar at 870 °C (Ellis & Green 1979). A= Harley & Green 1982; B = Harley 1984. T= temperature estimates in °C (Sen & Bhattacharaya 1984) at 14.5 kbar (Harley & Green 1982). X = average value.

	GO1	GO2	GO3	GO4	GO5	GO6	GO7	GO8	GO9
A:	15.0	14.9	15.0	16.8	14.4	13.5	14.4	12.2	16.4
B:	13.2	14.0	13.3	14.8	13.3	12.1	12.4	10.8	14.6
T:	869	954	876	861	884	900	851	906	863

$$X_A = 14.7 \text{ kbar}$$

$$X_B = 13.2 \text{ kbar}$$

$$X_T = 885 \text{ }^{\circ}\text{C}$$

11 Garnet - clinopyroxene (initial metamorphic mineral assemblage) temperature estimates (Ellis & Green 1979). P = 14.5 kbar (Harley & Green 1982).

	GC1	GC2	GC3	GC4	GC5	GC6	GC7	GC8	GC9	GC10	GC11
T=	850	885	828	901	879	882	895	835	907	832	852
K_D =	3.7	3.8	4.2	3.6	3.8	3.9	3.7	4.1	3.6	4.2	3.9

$$X_T = 868 \text{ }^{\circ}\text{C}.$$

$$X_{KD} = 3.9$$

8 Orthopyroxene - clinopyroxene (secondary metamorphic mineral assemblage) temperature estimates (Wells 1977).

	OC1	OC2	OC3	OC4	OC5	OC6	OC7	OC8
T =	750	736	722	673	745	674	717	692

$$X_T = 714 \text{ }^{\circ}\text{C}.$$

Interpretation of microtextures and mineral reactions.

The interpretation of microtextures on a scale of 1-100 microns is largely based on electron microscope work, where backscatter electron images give excellently detailed information of reaction relationships. The rock samples, on which this detailed study was based upon, are well preserved and free of late stage hydrated minerals. The reactions took place essentially along grain boundaries, and affected volumes only a few millimetres across. We found no evidence suggesting open-system chemical behaviour within the small reaction domains, and therefore, we consider the reaction systems to be isochemical. However, this conclusion does not apply either to the formation of the amphiboles seen in some symplectites, or to late stage hydration reactions, which were certainly not isochemical.

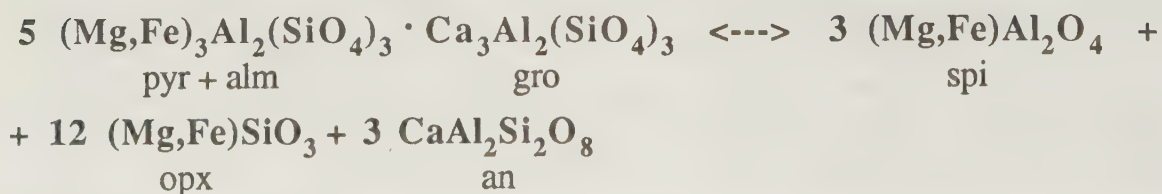
Where preserved, the initial metamorphic assemblages appear to have attained chemical equilibrium. Characteristic are large, chemically unzoned grains of clinopyroxene, kyanite and garnet or orthopyroxene, garnet and clinopyroxene. The grain boundaries are straight and undisturbed. These assemblages represent high-pressure granulite facies conditions (Green & Ringwood 1967, 1972), which is also confirmed by our PT -estimates.

In the sapphirine-bearing rock, the initial assemblage clinopyroxene - kyanite - garnet is to a large extent replaced by secondary assemblages, described above. The anhydrous nature of the secondary minerals, the chemical features such as marked zoning in plagioclase domains and abundant micro-scale symplectitic reaction rims indicate low P_{H_2O} and limited diffusion even over small distances. Equilibrium among secondary minerals apparently was not attained.

A sequence of mineral reactions can be deduced to explain the secondary textures. Although an unambiguous chronological order for the reactions cannot be established from the textural relationships alone, our reaction model requires the order in which we will present them in the text. In some cases, the reaction may have proceeded simultaneously.

Breakdown of pyrope rich garnet (Fig. 5):

This breakdown is illustrated by reaction (1):



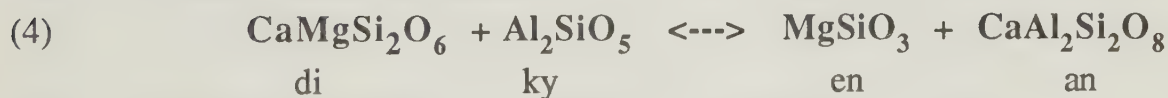
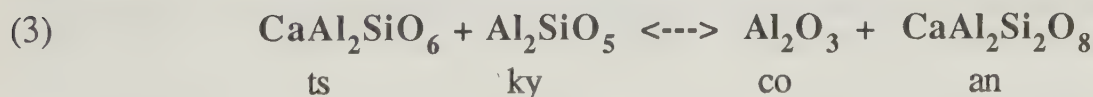
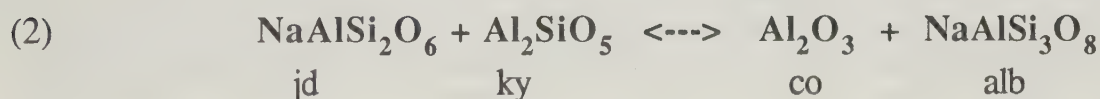
The reverse reaction is common at an intermediate stage in the formation of eclogites from basic, undersaturated, low pressure protoliths, and belongs to the intermediate pressure granulite facies (Green & Ringwood 1967). The gradual growth of garnet at the expense of orthopyroxene, spinel and plagioclase took place

in the pressure interval from 10.1 kbar to 11.3 kbar, or possibly up to 13.5 kbar, (i.e. over a pressure range of 1.2 - 3.4 kbar) at 1100 °C in the alkali poor olivine tholeiite (B) of Green & Ringwood (1967). Extrapolation of their data to temperatures around 800 °C indicates a first appearance of garnet at P around 11 kbar for oversaturated quartz-tholeiitic compositions with $Mg/(Mg+Fe^{2+}) = 0.90$. Lower values of the $Mg/(Mg+Fe^{2+})$ ratio cause garnet to form at lower pressures. In olivine-normative, undersaturated rocks, garnet appears at lower pressures than in quartz-normative compositions (Green & Ringwood 1967). It is therefore, reasonable to assume that in the undersaturated Kråkfjord rocks with $Mg/(Mg+Fe^{2+}) = 0.77-0.86$, reaction (1) took place at pressures around 10-13 kbar i.e. still within the stability field of kyanite.

The occurrence of spinel, formed by reaction (1), is often limited to the inner half of the symplectite rims around garnets. The symplectite generally becomes much coarser and poorer in spinel away from the garnet. This suggests that the symplectite phases recrystallize continuously, and that the spinel were consumed by reaction (6).

Clinopyroxene-kyanite breakdown:

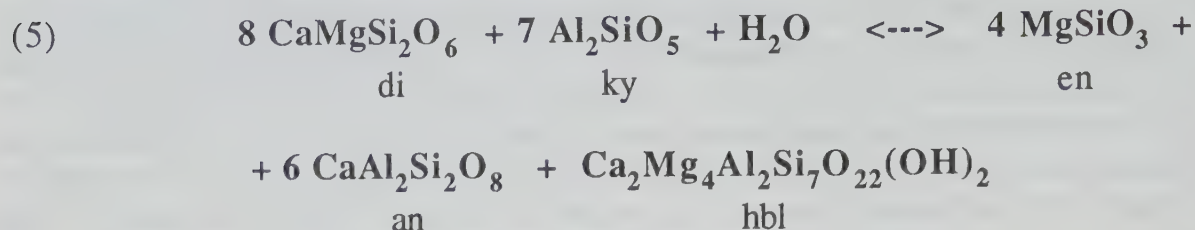
The next step in the breakdown of the initial metamorphic mineral assemblage affects the clinopyroxene and kyanite. These two minerals were never found in contact in the studied thin sections; they are always separated by the above described reaction domains. Therefore, a reaction relationship between clinopyroxene and kyanite is suggested. In the presence of kyanite, the three reactions below describe the breakdown of clinopyroxene, in terms of its components.



Reaction (2) explains the rim of albite rich plagioclase (andesine, Figs. 2,4) which, together with orthopyroxene formed in reaction 4, occurs as a symplectite around clinopyroxene. The 'andesine front' possibly represents the former clinopyroxene-kyanite boundary. Reactions (2) and (3) also give an explanation for the strongly variable modal corundum/sapphirine ratio which would have been expected to be more uniform if corundum and sapphirine had been formed only by reaction (6).

Within the orthopyroxene-plagioclase symplectite, there are minor

amounts of symplectitic amphibole. A likely explanation of its presence is a reaction similar to reaction (4) but occurring at higher P_{H_2O} :



Temperature estimates made on unzoned clinopyroxene rims / orthopyroxene symplectites, assuming equilibrium at least within a 30 micron wide zone along their mutual grain boundary, suggest T near 700°C. Because of the continuous nature of the composite reaction (2)+(3)+(4), the temperature recorded is interpreted as a 'frozen' minimum T for the breakdown of clinopyroxene.

Sapphirine-forming reactions:

A number of sapphirine-forming reactions can be proposed, but only a few of them are in accord with the textures and mineral chemistry of the studied rocks. Sapphirine occurs in the following textural contexts:

- A. Together with corundum, replacing kyanite (by far the most frequent texture, Fig. 2).
- B. Surrounding small, solitary grains of either spinel (fairly common), corundum, or spinel and corundum (Fig. 11).
- C. As rims separating small spinel grains from kyanite (not very common, Fig. 8).
- D. Replacing orthopyroxene + spinel symplectites around garnet (un-common, Fig. 10).
- E. Selectively replacing spinel inside orthopyroxene symplectites around garnet (rare, Fig. 10).

In cases A and C above, the formation of sapphirine clearly involves kyanite as one of the reactants. The alumina-rich sapphirine, 7:9:3 to peraluminous in composition, must have formed by a reaction of kyanite with another alumina-rich, ferromagnesian mineral. The only available mineral of this composition is spinel. In Fig. 8, sapphirine can be seen replacing both spinel and kyanite, at the same time efficiently shielding both the reactants from each other. The spinel consumed was formed by reaction (1). The presumed reaction is:



This reaction is illustrated by Fig. 3b. The Al_2O_3 released in this reaction is at least partly incorporated in sapphirine to form a peraluminous mineral variety. Relict grains of kyanite are almost always present among the reaction products and thus the amount of spinel is the limiting factor in extent to which reaction (6) progresses. In the kyanite-free parts of the Kråkfjord metabasite, spinel is a common phase and sapphirine is never present.

Sapphirine-forming reactions between spinel and Al-silicates have been described by Nixon et al. (1973) from Labwor, Uganda. These authors also discussed the frequently suggested reaction between quartz and spinel, but concluded that a more alumina-rich mineral is needed to produce peraluminous sapphirine; in their rocks this mineral is sillimanite. Schreyer et al. (1975) described the replacement of kyanite by sapphirine in kornerupine-bearing rocks from Walheim, Saxony (G.D.R.), but did not suggest any specific reaction.

Experimentally derived P,T-brackets for reaction (6) are not available in the literature. Kiseleva (1976) pointed out the importance of using natural ordered (in contrary to synthetic disordered) sapphirine for calculations of equilibria. Due to the absence of thermodynamic data on natural ordered 7:9:3 sapphirine in internally consistent data sets containing also kyanite, spinel and corundum, it is difficult to theoretically calculate the equilibrium conditions with a reasonable degree of certainty. An attempt to estimate the PT-conditions of reaction (6) (pure phases) by taking entropies, enthalpies and thermal expansion constants for natural ordered sapphirine in the $\text{MgO-Al}_2\text{O}_3\text{-SiO}_2$ -system published by Kiseleva (1976) and combining them with thermodynamic data for kyanite, spinel and corundum from Robie et al. (1979), gave as result the dashed line C in Fig. 14. At 25°C, this equilibrium was found to lie at 14.8 kbars pressure with a gentle negative slope of -0.70 bar/K. At 800 °C the same data set gives 10.3 kbar and a slope of -20 bar/K. However, attempts to calculate other, theoretically possible, reactions in the same three-component, five-phase system (the phases listed above plus enstatite) yields a completely meaningless arrangement of the equilibrium curves.

The same data set was also combined with the heat capacity equations of Berman & Brown (1985) in order to obtain better extrapolations to high temperatures. The equilibrium of reaction (6) was then found to lie at very low temperatures (around 100 °C at 13 kbar) with sapphirine + corundum on the low temperature side, which is not in accordance with the observed relationships in the Kråkfjord rocks. A combination of the same data from Kiseleva (1976) on sapphirine, with entropies, enthalpies and thermal expansion equations taken from Helgesson et al. (1978) yielded unrealistically high pressures.

Thus, these calculations of reactions involving sapphirine are liable to very severe uncertainties. Therefore, we can only conclude that in the temperature range around 700 °C and at pressures around 8-10 kbar the Kråkfjord rocks were on the

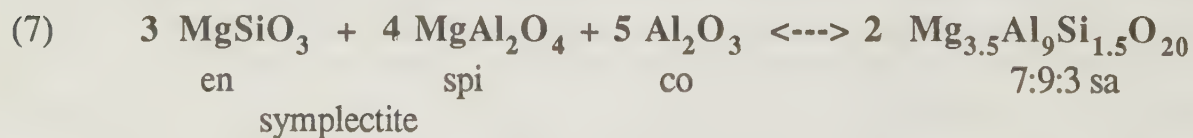
low pressure side of reaction (6) (Fig. 14). The position of equilibrium (6) in the PT-field probably lie somewhere at or above the stippled line C in Fig. 14. In the Kråkfjord rocks the effect of Fe for Mg and Cr for Al substitutions in spinel and sapphirine would be expected to expand the stability field of spinel and kyanite towards lower pressures and temperatures, compared to the position of the curve in the pure MgO-Al₂O₃-SiO₂ system.

Seifert (1974) concluded that the tie-line spinel - Al-silicate is restricted to extremely high temperatures in the synthetic MgO-Al₂O₃-SiO₂-H₂O system, whereas in natural rocks the coexistence of spinel and andalusite / sillimanite proved it to be stable also at much lower temperatures. Schreyer (1967) found no stable tie-line spinel-kyanite in a study of the same system at pressures between 10 and 25 kbar. Thus the present knowledge of the stable coexistence of spinel and Al-silicates is inadequate.

Not only spinel but also orthopyroxene from the symplectites around garnets was in a few cases consumed in the formation of sapphirine. This took place in those parts of the symplectites which are very close to kyanite. In Fig. 9, orthopyroxene is partly replaced by sapphirine. Rarely, a selective replacement of symplectitic spinel by sapphirine occurs within the orthopyroxene symplectite (Fig. 10).

Sapphirine in symplectites together with orthopyroxene and spinel has been described in silica-deficient granulites from Ganguvarpatti, Madurai, southern India (Muthuswami 1949; Grew 1982; Mohan 1985). Mohan (1985) described symplectites of cordierite + orthopyroxene + sapphirine + spinel/hercynite/magnetite which formed in response to hydration and oxidation of garnet. In the Kråkfjord rocks, however, sapphirine is not formed directly by garnet breakdown but on the expense of spinel ± orthopyroxene which are reaction products of the garnet breakdown (reaction (1)). Around one and the same garnet, sapphirine only occurs in the part of the symplectite facing sapphirine+corundum domains around kyanite, whereas the opx+spi symplectites are well preserved along the part of the garnet which faces away from kyanite.

The replacement and sometimes complete disappearance of the orthopyroxene-spinel symplectite and also the replacement of corundum (Fig. 11) can be explained by the incompatibility of these three phases when sapphirine becomes stable. The ensuing reaction is:

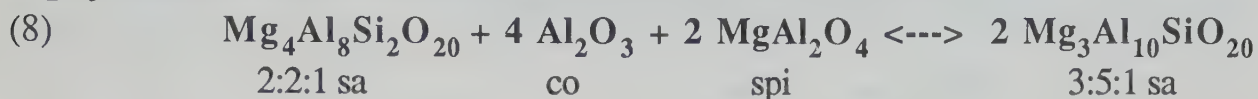


This reaction is graphically presented in Fig. 3c.

In an experimental investigation of the system MgO-Al₂O₃-SiO₂-H₂O, Schreyer (1967) found that the assemblage enstatite + spinel + corundum was a shortlived, metastable mineral association yielding sapphirine at 15 kbar and 900°C. If this is valid also at lower pressures and temperatures, reaction (7) could be responsible for the formation of sapphirine at the expense of orthopyroxene and

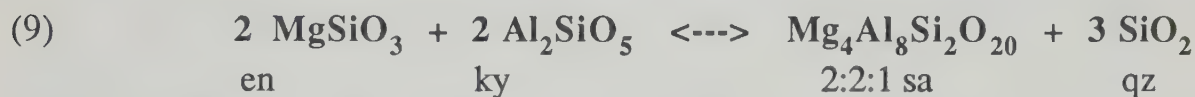
corundum, which is not explained by reaction (6).

The Al-contents of the Kråkfjord sapphirines are variable. (Fig. 12, Table 3). It is commonly noted that the composition of sapphirine reflects the micro-geochemical environment, i.e. sapphirine in aluminous systems or in contact with aluminous phases is saturated in Al_2O_3 . In the Kråkfjord rocks, sapphirine occurs together with the alumina-rich phases corundum, spinel and kyanite. The Al_2O_3 content of sapphirine may be controlled by equilibrium :



This equilibrium has been described by Droop & Bucher-Nurminen (1984), who among others (Lal et al. 1978) recorded a micro-chemical environmental control of the Al-contents in sapphirine.

We have also considered a possible reaction between enstatite and kyanite:



The sillimanite version of this reaction has been investigated experimentally by Chatterjee & Schreyer (1972) and Newton et al. (1974). Droop & Bucher-Nurminen (1984) tried to calculate equilibria involving pyrope, sapphirine, kyanite, enstatite and quartz for granulites from the Gruf Complex of the Italian central Alps. They concluded that their data set could not be made consistent with various experimental reversals (e.g. Chatterjee & Schreyer 1972) and neither with the Al_2SiO_5 phase diagram. They pointed out that "the data derived for sapphirine from experimentally studied equilibria necessarily refer to disordered sapphirine (Kiseleva, 1976). In applying data to the Gruf rocks with natural ordered sapphirine serious uncertainties may therefore be introduced with respect to the positions of solid-solid reactions involving sapphirine". However, they recalculated the sillimanite reaction of Chatterjee and Schreyer (1972) for kyanite by extrapolating the experimentally determined data of the sillimanite version to lower temperatures, allowing for the kyanite-sillimanite inversion and impurities in the reaction phases ($\text{Mg}/(\text{Mg}+\text{Fe}^{2+}) = 0.80-0.86$ for sapphirine and sapphirine-enstatite $\text{KD}_{\text{Fe-Mg}} = 1.11$). The position of their line is indicated in Fig. 14 by the dashed line D.

Their results make it tempting to suggest that reaction (9) occurred in the Kråkfjord rocks. However, neither 2:2:1 sapphirine nor quartz were found in the thin sections studied, and this makes it unlikely that reaction (9) took place in the Kråkfjord rocks. We emphasize that reactions (6) to (8) could have followed more complex paths involving additional components with local chemical interactions between neighbouring phases. An excellent example are the most Cr-rich sapphirines which are always found in the vicinity of small chrome-rich spinels. These spinels occur preferentially in the plagioclase domains separating sapphirine,

anorthite and corundum symplectites from garnets and clinopyroxenes. They have strongly varying Cr-contents and most likely represent a remnant spinel phase where Cr, Fe and Zn have been enriched by reactions (6) to (8).

P T evolution

This paper treats the details of just one stage, the early retrogression, in the following discernible evolution of the Kråkfjord rocks:

A: Origin as a layered low P intrusion.

B1: Progressive metamorphism.

B2: High P granulite metamorphism.

C1: Early retrogression at low P_{H_2O} . (The stage treated in this paper)

C2: Late retrogression at high P_{H_2O} .

No igneous minerals are preserved, but the whole-rock chemistry and field relations suggests an origin as a plagioclase- and olivine-bearing layered intrusive rock (cf. Bulk Chemistry).

In the Brandsfjord sapphirine-bearing rocks (Fig. 1), a progressive metamorphism (stage B1) is evident from numerous inclusions of plagioclase, quartz and zoisite in garnet cores. The garnets show a marked increase in pyrope content (from 26 to 53 mole-%) from core to rim, whereas Fe, Mn and Ca decrease. The Brandsfjord garnet rims are identical in composition to the unzoned garnets in the Kråkfjord sapphirine bearing rock. The Brandsfjord garnets were later replaced by symplectitic orthopyroxene, spinel and anorthite, exactly as at Kråkfjord.

Stage B2 is characterized by cpx - ky - gt and opx - gt - cpx assemblages which equilibrated at P T-conditions around 14.5 kbar and 870 °C.

During C1 the peak stage was followed by low P_{H_2O} retrogression processes treated in this paper. The fifth and final stage, C2, included extensive hydration often guided by shearing and boudinage of the primary layering.

The C1 reaction sequence described above can to some extent be visualized as the PT-path shown in Fig. 14. Its construction is essentially based on observations of different mineral assemblages, textural relationships and on the geobarometry/geothermometry presented earlier in this paper. The thermodynamic calculation for reaction (6) represented by dashed curve C in Fig. 14, is consistent with the PT-path deduced from geothermobarometry and textural relations, but as pointed out above, thermodynamic calculations for the sapphirine-

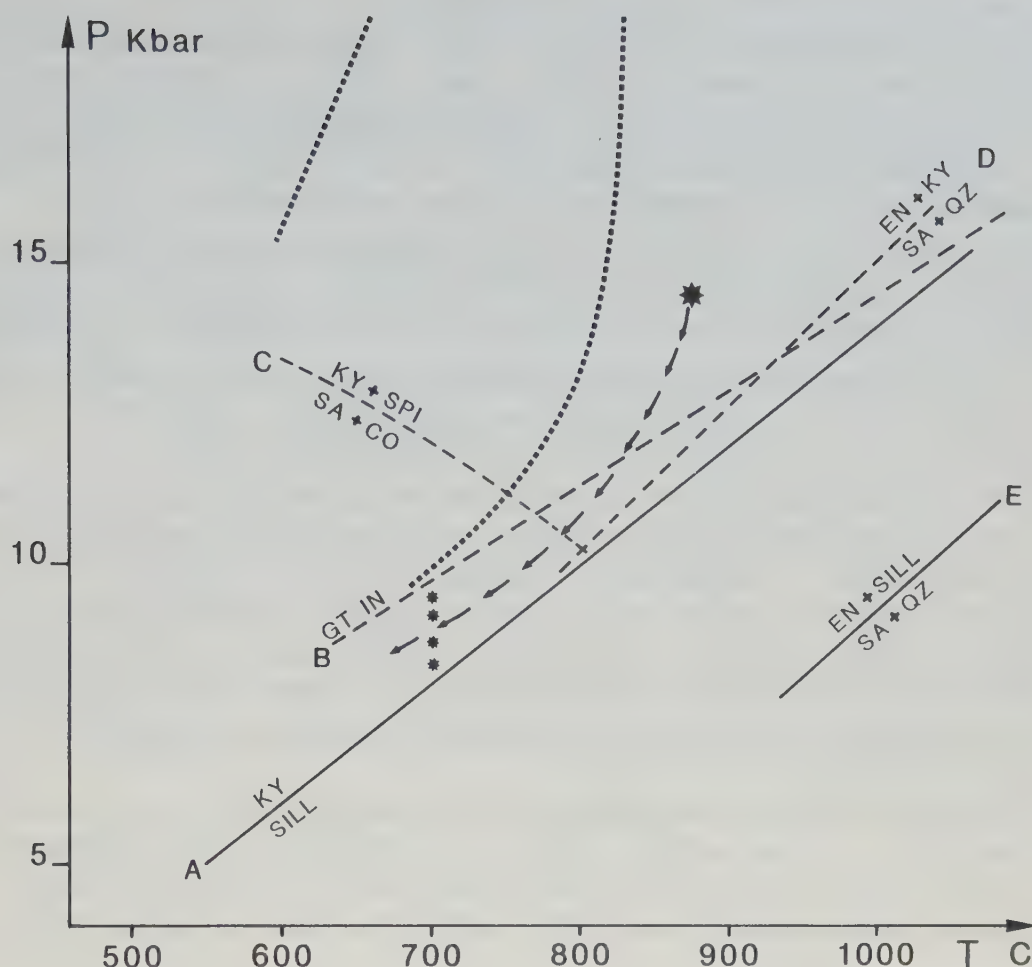


Fig. 14. Pressure and temperature relationships for the Kråkfjord sapphirine-bearing rocks. 'A' marks the kyanite - sillimanite boundary of Holdaway (1971). 'B' denotes the extrapolation of the first appearance of garnet in quartz tholeiites with $Mg/(Mg+Fe^{2+}) = 0.90$ (Green & Ringwood 1967). The dashed curve 'C' indicates the equilibrium kyanite + spinel $\leftrightarrow$ 7:9:3 sapphirine + corundum for pure Mg-phases as described in the text (p.VI-25). The dashed curve 'D' indicates the equilibrium kyanite + enstatite $\leftrightarrow$ 2:2:1 sapphirine + quartz of Droop & Bucher-Nurminen (1984). The curve 'E' marks the equilibrium enstatite + sillimanite $\leftrightarrow$ 2:2:1 sapphirine + quartz of Chatterjee & Schreyer 1972, Kleppa & Newton 1975. The lower end of this line represents the invariant point calculated by Kleppa & Newton (1975).

Stars indicate calculated PT-conditions for the peak metamorphic assemblage using the thermometer of Ellis & Green (1979) and the barometer of Harley & Green (1982), and minimum temperatures for the breakdown of clinopyroxene as calculated by the thermometer of Wells (1977). Arrows indicate the proposed retrograde PT-path for the Kråkfjord sapphirine-bearing rocks.

The stippled line delimits the field of calculated P-T-values for eclogites and related rocks in the southern and central Western Gneiss Region (deduced from the data of Griffin et al. 1985).

forming reactions are liable to large uncertainties.

Kyanite is apparently the stable Al-silicate. Sillimanite has not been found in any of the thin sections from the Kråkfjord area. This is in contrast to the gneiss terrain just east of the Roan peninsula, where sillimanite has been found to replace kyanite. The gneiss terrain further east may represent a higher tectonostratigraphic level characterized by lower pressures during the retrogression.

The peak PT-values and the low- P_{H_2O} retrogression path outlined for the Kråkfjord rocks can be compared to peak PT-values and retrogression paths for the classical eclogite - granulite terrains further south in the Western Gneiss Region of Norway. The stippled line in Fig. 14 delimits the field of calculated PT-values for eclogites, granulites and peridotites in the southern and central Western Gneiss Region as deduced from the data of Griffin et al. (1985).

The Kråkfjord peak PT-value plots within the same range as the southern and central Western Gneiss Region with respect to pressure, but indicates somewhat higher temperatures. A comparison of retrogression paths shows that they have similar shapes featuring initial steep parts, indicating a marked decompression, followed by a less inclined part which imply cooling within a restricted pressure interval. Studies of retrograde assemblages from the Western Gneiss Region suggest that the post-metamorphic uplift was initially adiabatic (Krogh 1977, 1982; Carswell et al 1982; Griffin et al. 1985).

The present study of the Kråkfjord sapphirine bearing rocks, demonstrates that at least parts of the northern segment, Vestranden, of the Western Gneiss Region went through a high PT-metamorphism and uplift history similar to the Caledonian one in the southern and central parts of the Western Gneiss Region.

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PAPER VII

MEGA-LENSES AND SCANDIAN DEFORMATION IN BASEMENT IN THE
NORTHERN PART OF WESTERN GNEISS REGION, VESTRANDEN,
CENTRAL NORWEGIAN CALEDONIDES.

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MEGA-LENSES AND SCANDIAN DEFORMATION IN BASEMENT IN THE NORTHERN PART OF WESTERN GNEISS REGION, VESTRANDEN, CENTRAL NORWEGIAN CALEDONIDES.

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Abstract

A large scale (meter to hundreds of meter thick bands) compositional banding can be seen in the westernmost part of Vestranden. The banding formed due to very intense shear deformation of migmatitic granitoids and basic rocks. Also rocks supracrustal origin is found within the banded gneisses. The gneisses are multiply folded and a complex interference pattern is seen (Fig. 1). Less deformed gneisses occur as lens-shaped areas of varying size in the banded gneisses. The rocks in the internal parts of the lenses are well preserved. In one of these lenses, the Granhol vatnet lens, coronitic metabasites occur together with two generations of migmatite neosomes. The neosomes in the margin of the lens are attenuated and the coronitic rocks are retrogressed. Radiometric dating of a granite dyke intruding supracrustal rocks in the western Vestranden indicate that the major deformation and folding took place after approximately 430 Ma (Scandian). Granulite facies metamorphism in western Vestranden occurred prior to this deformation.

Introduction

The Vestranden area is the northernmost extension of the Western Gneiss Region in Norway (fig.1) and the westernmost area where it is possible to study the basement on land in the central part of the mountain belt. This part of the Baltic cratonic margin suffered intense Caledonian deformation and metamorphism. Several of the Precambrian crystalline units now incorporated in the Caledonian nappes further east were probably derived from a basement of Vestranden type, which lay to the west of the present coastline. Thrusting of basement and miogeoclinal sediments, originating from west of the present coastline, occurred as early as 485 Ma (Claesson 1980), showing that the westernmost basement of the cratonic margin, beneath the miogeocline, was involved in the early Caledonian deformation.

Starting in the Grong-Olden Culmination in the east, it is possible to almost continuously study deformation and metamorphism within the basement over a distance of about 200 km across the strike of the orogen. A westwards-increasing metamorphism and deformation ("Caledonization") is commonly recognized in the basement. The western part of Vestranden is characterised by high positive magnetic and gravimetric anomaly-patterns compared to areas further east. It is also partly of a higher metamorphic grade locally reaching granulite facies PT conditions.

Western Vestranden consists of a complex of migmatitic gneisses ranging from granite to tonalite in composition. Numerous basic rocks in the form of dykes,

boudins, irregular layers and small gabbro massifs occur in the migmatites. Some of the basic rocks have a high pressure granulite mineralogy. (Johansson & Möller in press.). Both prograde and retrograde parageneses have been recognized. Also rocks of supracrustal origin occur in the Vestranden area. These rocks are folded together with the underlying migmatitic rocks. Supracrustal rocks can at least in one place, Fossilia to 50 km NE of Roan, be correlated with rocks of the Gula Nappe. The correlation is based on lithological similarities and a radiometric dating of a granitic dyke. The U-Pb zircon age of the dyke is 430 ± 12 Ma implying a Scandian thrust emplacement of these supracrustal rocks.

The most striking tectonic feature of the western Vestranden, a prominent compositional banding consisting of alternating bands of granitoid gneisses and basic rocks is isoclinally folded and refolded with development of complex interference pattern (Fig. 1). The folds have wavelengths up to at least two kilometres. This gneiss complex overlies the Roan dome (Fig. 1). The relation between the gneiss complex and the Roan dome is discussed by Möller (1986)

The Granholvatnet lens

In the Granholvatnet area north of the Roan peninsula (Fig. 1) a large lens can be seen on the aerial photos. The Granholvatnet lens is approximately 500 m thick and 2800 m long in the present erosion surface and limited by intense shear zones passing out into the banded gneisses. The lens is concordant to the surrounding banding and consists of the same rock types as those found outside the lens i.e. red and grey migmatitic gneisses with minor amounts of basic rocks. Also a small lens (< 100 m long) of ultramafic rocks occurs within the banding south of the Granholvatnet lens (Fig. 2).

The internal structures of the Granholvatnet lens can be studied in an approximately 1000 m long continuous section along a road through the lens (Fig. 3). Deformation decreases gradually towards the centre of the lens. Along the margins of the lens all older fabrics are transposed into very intense foliations seen in the surrounding gneisses. The basic rocks are here strongly flattened, isoclinally folded and generally concordant to the foliation in the gneiss (Fig. 3 A). No igneous minerals are preserved in the basic rocks. In ductile shearzones the migmatitic veins are commonly attenuated to thin bands (Fig. 3 B).

The centre of the lens is partly structurally chaotic with irregular migmatitic veins (Fig. 3 D) and fragmented basic rocks (Fig. 3 C), some with coronitic textures. Two generations of migmatitic veins occur. The younger generation is similar to that found in the Roan peninsula (Möller in prep.) where it is an important structural time marker. The occurrence of well preserved basic rocks with coronitic textures in the Granholvatnet lens indicates that the high-grade metamorphism pre-dated the major deformation that led to the formation of banding, folding and retrogression.

It has been shown elsewhere (Johansson et al. this volume) that the deformation of cover rocks at least locally is of Scandian age. General concordance of the banding in the gneisses and the foliation in the cover units suggests that the

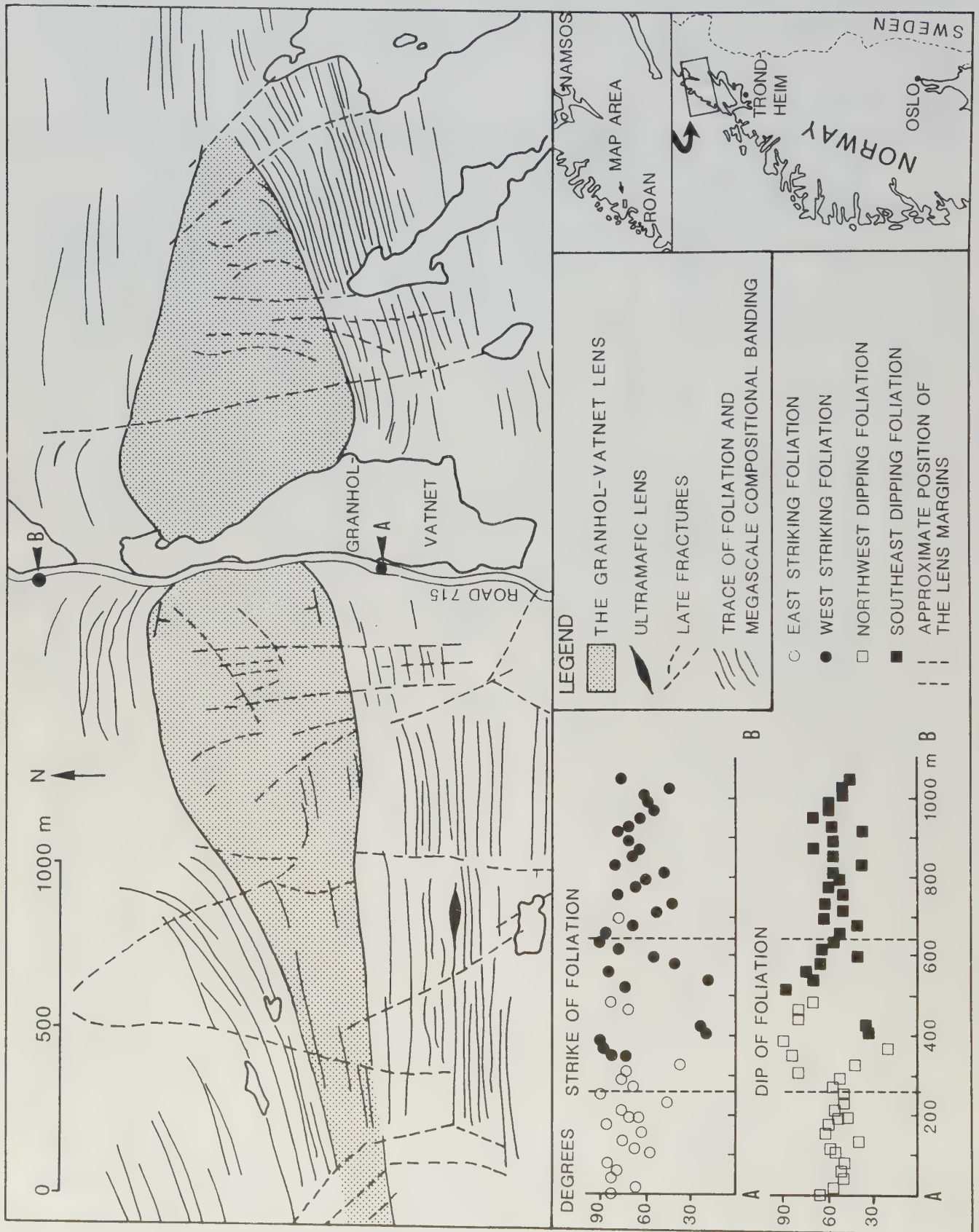


Fig. 2. Lineament and fracture pattern around the Granholvatnet based on photo-interpretation. Strikes and dips of the regional foliation shown below the map were measured along profile A-B.

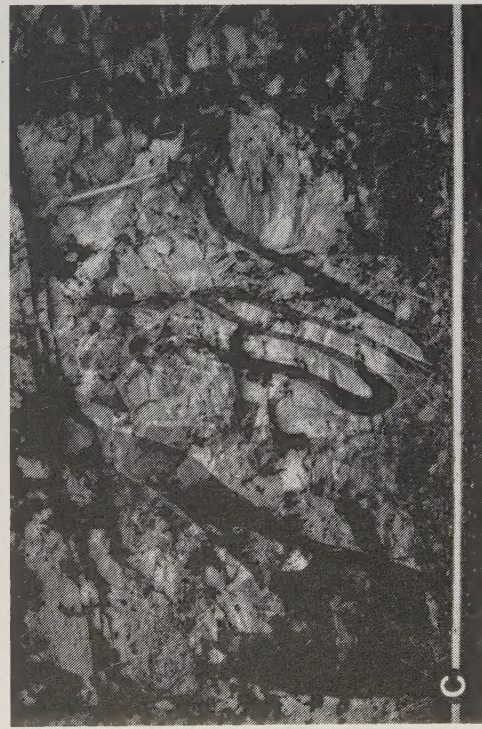
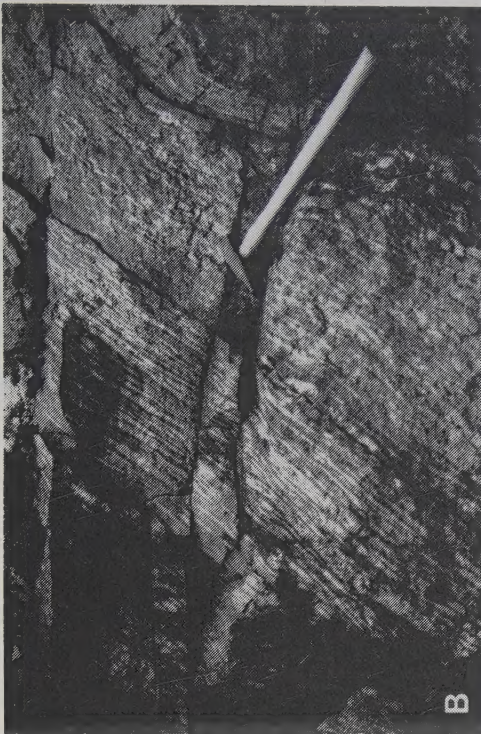


Fig. 3. A: Sheared migmatite with isoclinally folded metabasites (at the arrows) at the northern margin of the Granholvatnet lens. B: Veined migmatite transposed into a planar secondary foliation at the northern margin of the lens. C: Irregular and folded fragments of metabasites in the centre of the lens. D: Comparatively well preserved migmatite veins in the centre of the lens. The length of the hammer is 55 cm.

development of the former also is of Scandian age.

The local preservation of early structures and metamorphic parageneses shows that not even the westernmost parts of the Vestranden area are completely "Caledonized" by the Scandian deformation and metamorphism. Several areas consisting of less reworked basement bounded by intensely deformed basement locally interbanded with supracrustal rocks occur in Vestranden. These less deformed areas could be regarded as "windows through time". Detailed metamorphic and structural investigations together with isotope studies of these areas is therefore an important task of future research in the westernmost basement of the Baltic Shield.

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